The Community Hydrology (and Biophysics) Project: CLM3.5

Keith Oleson, Reto Stöckli, Guo-Yue Niu, Peter Thornton, Liang Yang
Peter Lawrence, Sam Levis, David Lawrence,
Aiguo Dai, Taotao Qian, Steve Running,
Gordon Bonan, Bob Dickinson, Scott Denning

Nan Rosenbloom, Erik Kluzek

Numerous funding sources: NSF, DOE, and NASA as well as NCAR initiatives (Biogeosciences, Water Cycle, Impacts Assessment)

What distinguishes a land model within a GCM consisting of so many important pieces?

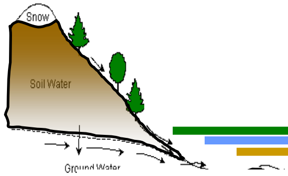
The land surface is a critical interface through which climate change impacts humans and ecosystems

and

through which humans and ecosystems can effect global environmental change

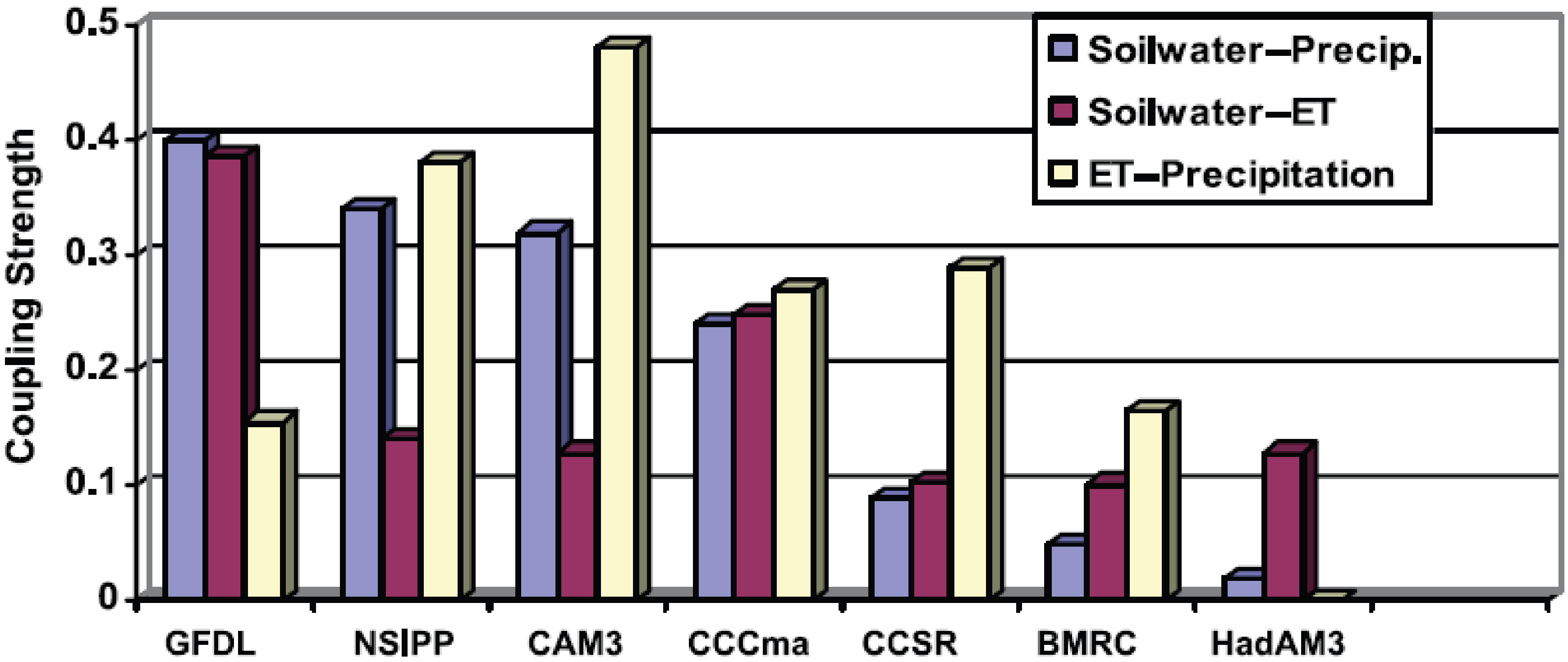
Land processes in climate research

- **Energy, water, and momentum fluxes;**
  flux partitioning (sensible vs latent heat); albedo; runoff to ocean



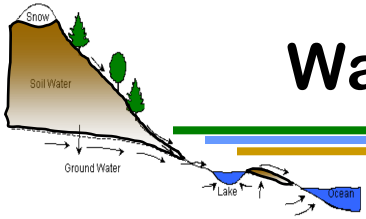
Land-atmosphere interactions

GLACE: To what extent does soil moisture influence the overlying atmosphere and the generation of precipitation?



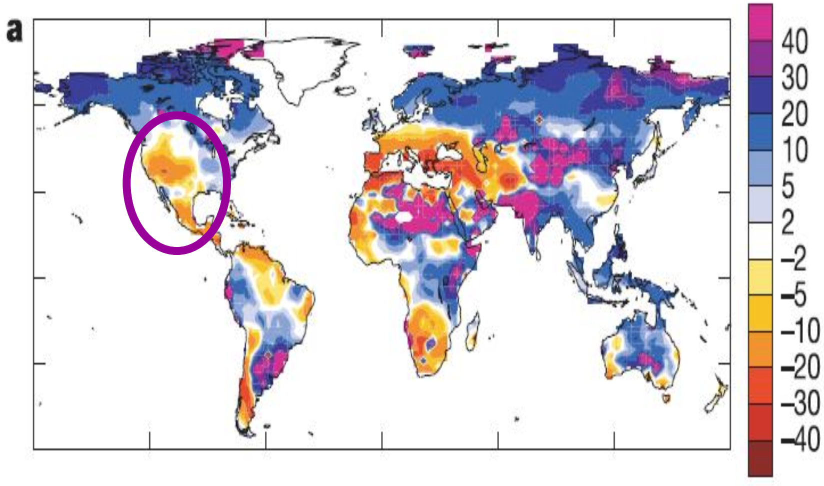
How does the representation of land-atmosphere interactions affect simulation of droughts, floods, extremes?

Koster et al., 2004; IPCC

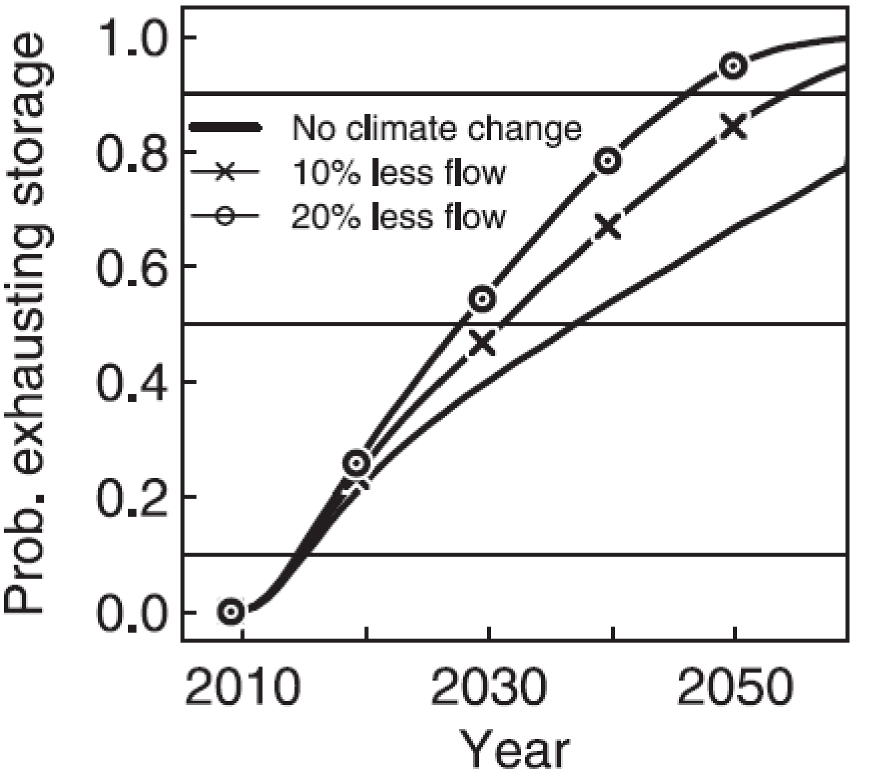


Water resources: When will Lake Mead go dry?

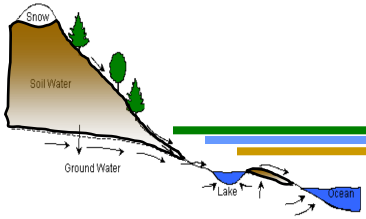
% Change in Runoff by 2050 (A1B)



Milly et al., 2005

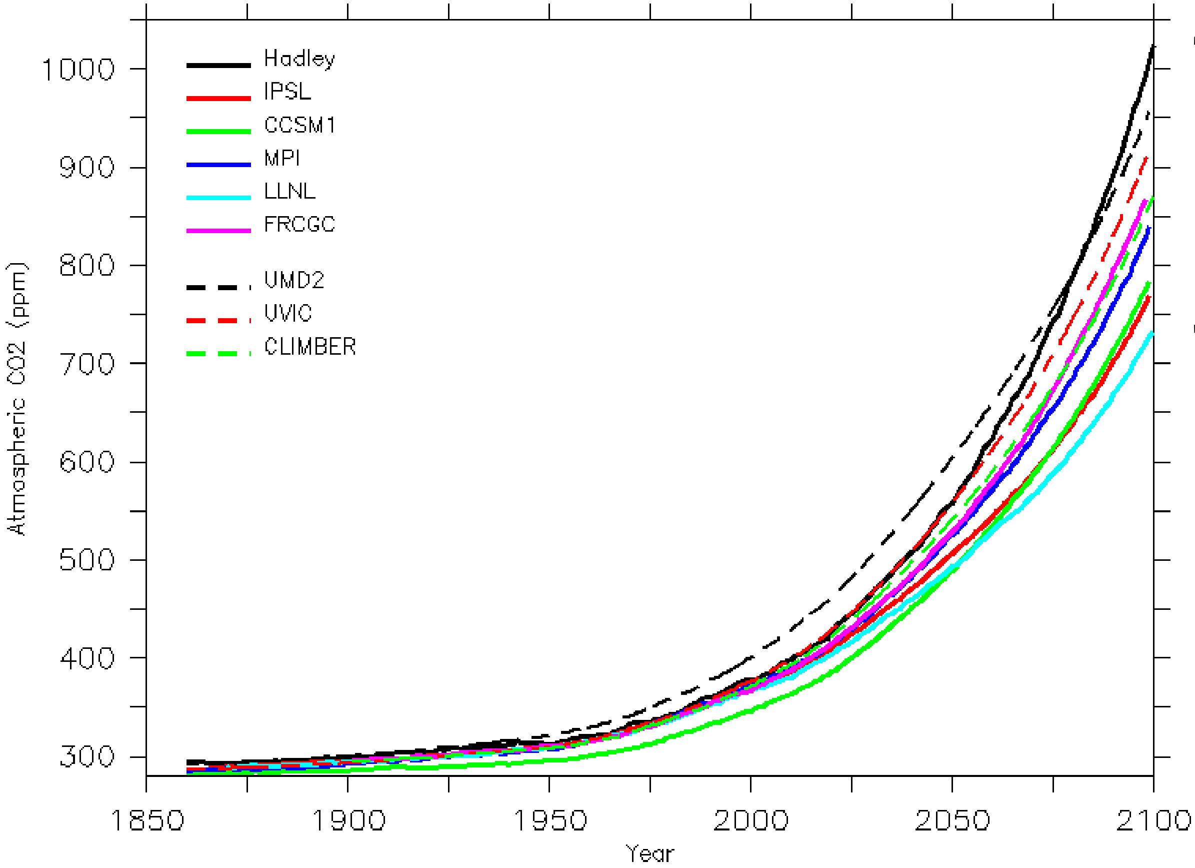


Barnett et al., 2008



C4MIP – Climate and carbon cycle

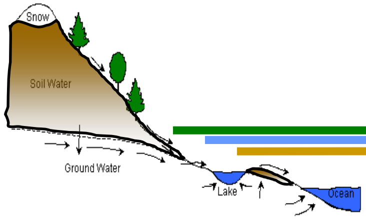
Atmospheric CO_2 concentration



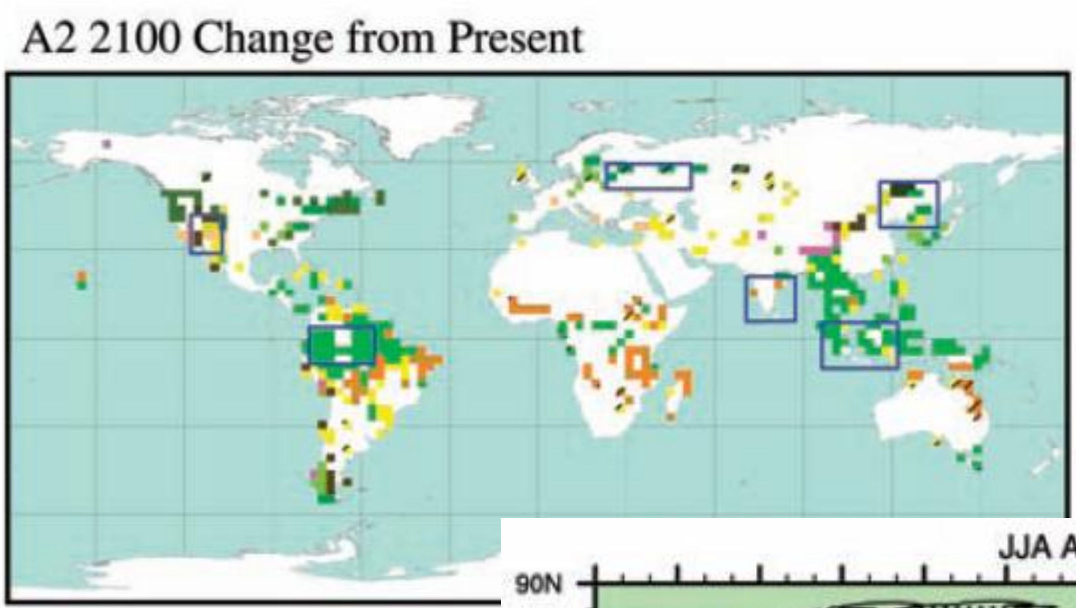
> 250ppm spread

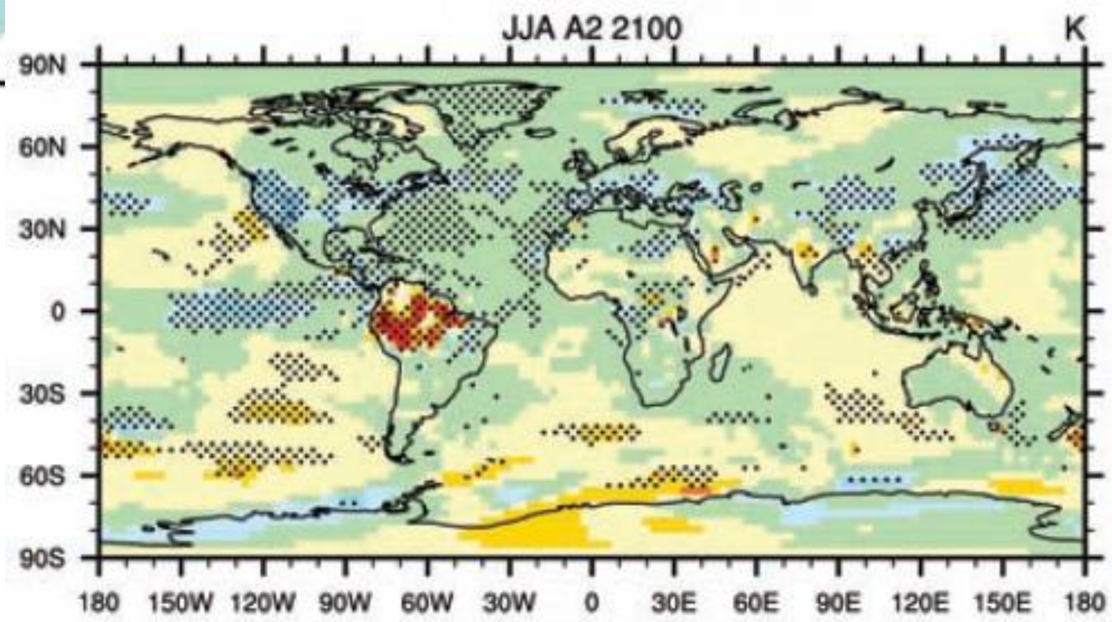
How does nitrogen cycle alter climate-carbon cycle feedbacks?

Courtesy of Pierre Friedlingstein

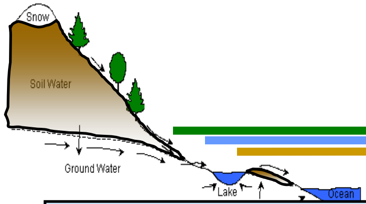


Land cover/land use change





Feddema, 2005



Integrated effects of land cover change

Biogeophysical

A2 – cooling with widespread cropland

B1 – warming with temperate reforestation

Biogeochemical

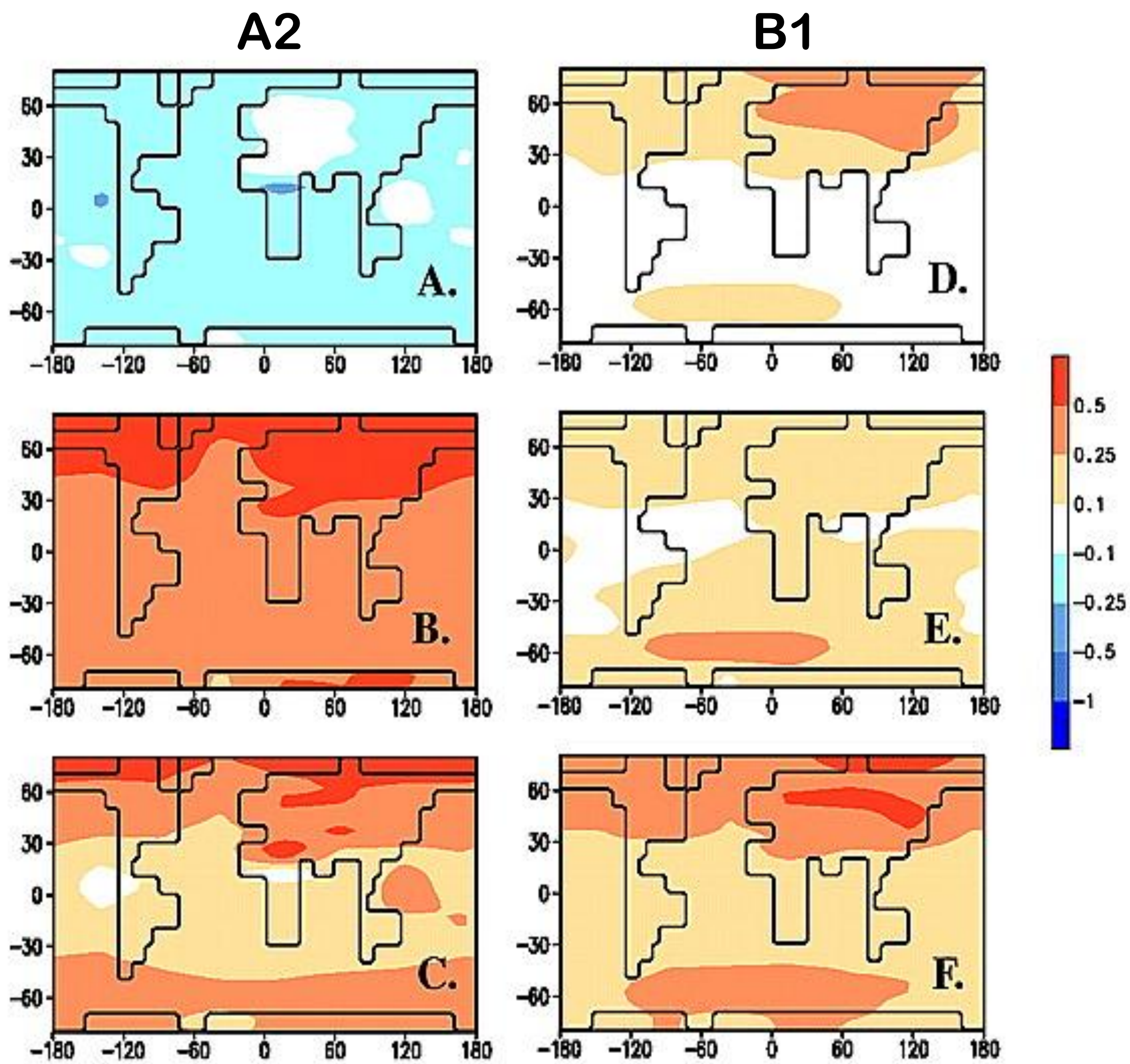
A2 – large warming; widespread deforestation

B1 – weak warming; less tropical deforestation, temperate reforestation

Net effect

A2 – BGC warming offsets BGP cooling

B1 – moderate BGP warming augments weak BGC warming



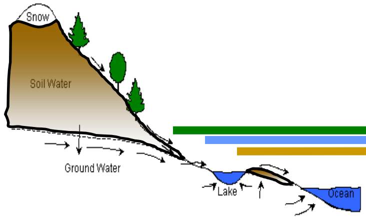
Sitch et al., 2005

Land processes in climate research

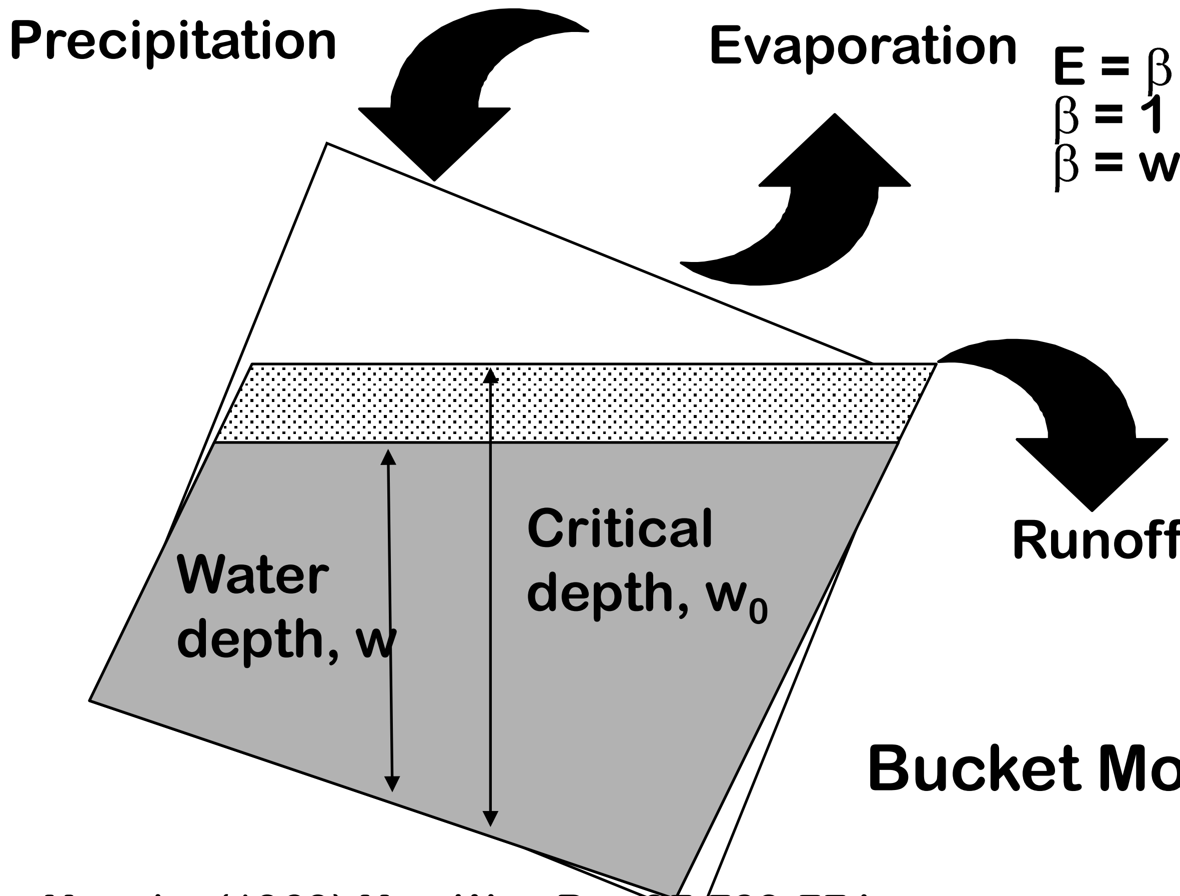
- Land-atmosphere interaction
- Water resources
- Land cover/land use
- Terrestrial carbon cycle, dynamic vegetation biogeography
- Fire, dust, permafrost
- Geoengineering

All related to hydrology and biophysics of the model

Some History



1st Generation: Bucket Model

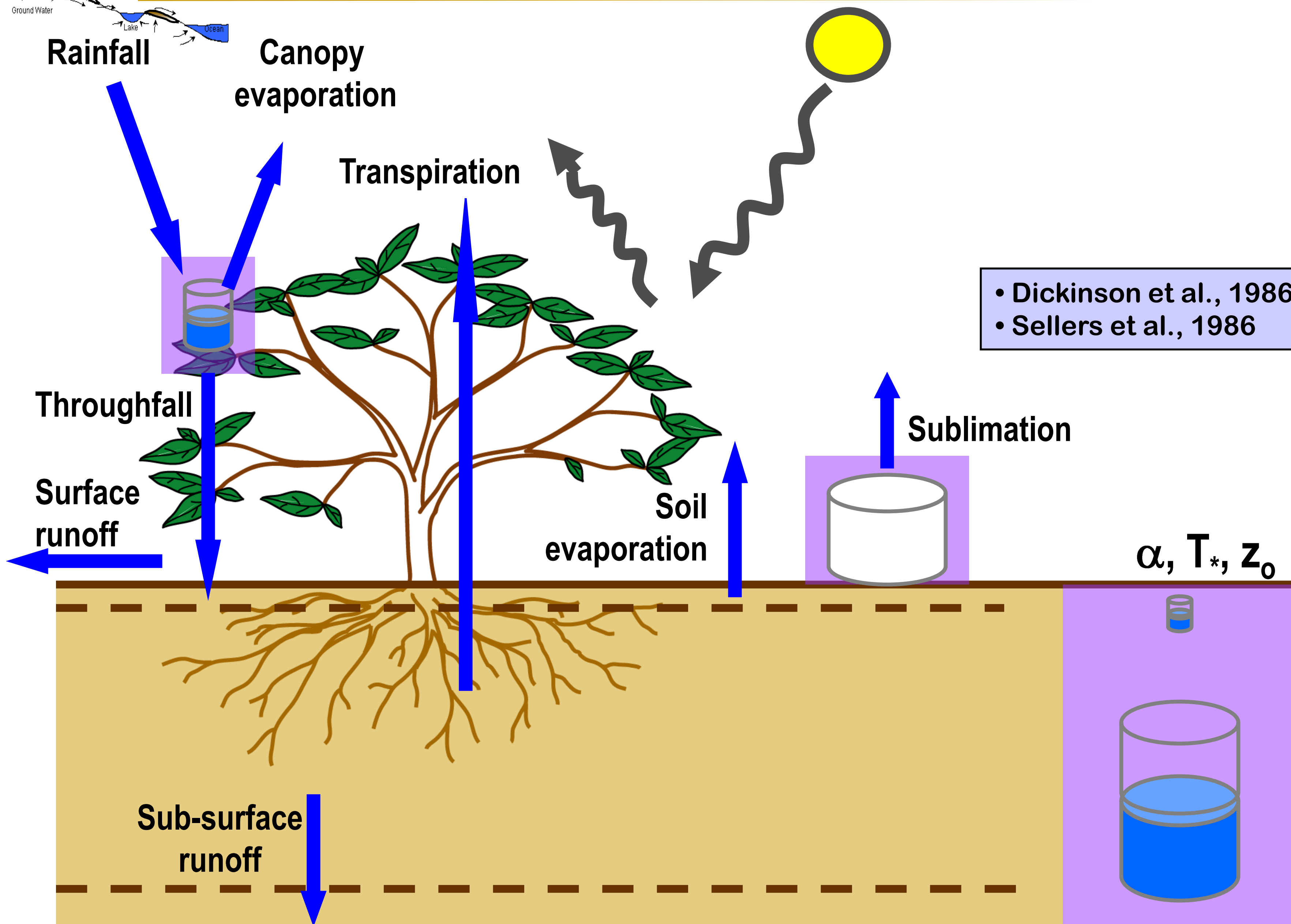


$E = \beta E_p$
$\beta = 1 \quad \text{for } w \geq w_0$
$\beta = w/w_0 \text{ for } w < w_0$

Manabe (1969) Mon Wea Rev 97:739-774
Williamson et al. (1987) NCAR/TN-285+STR

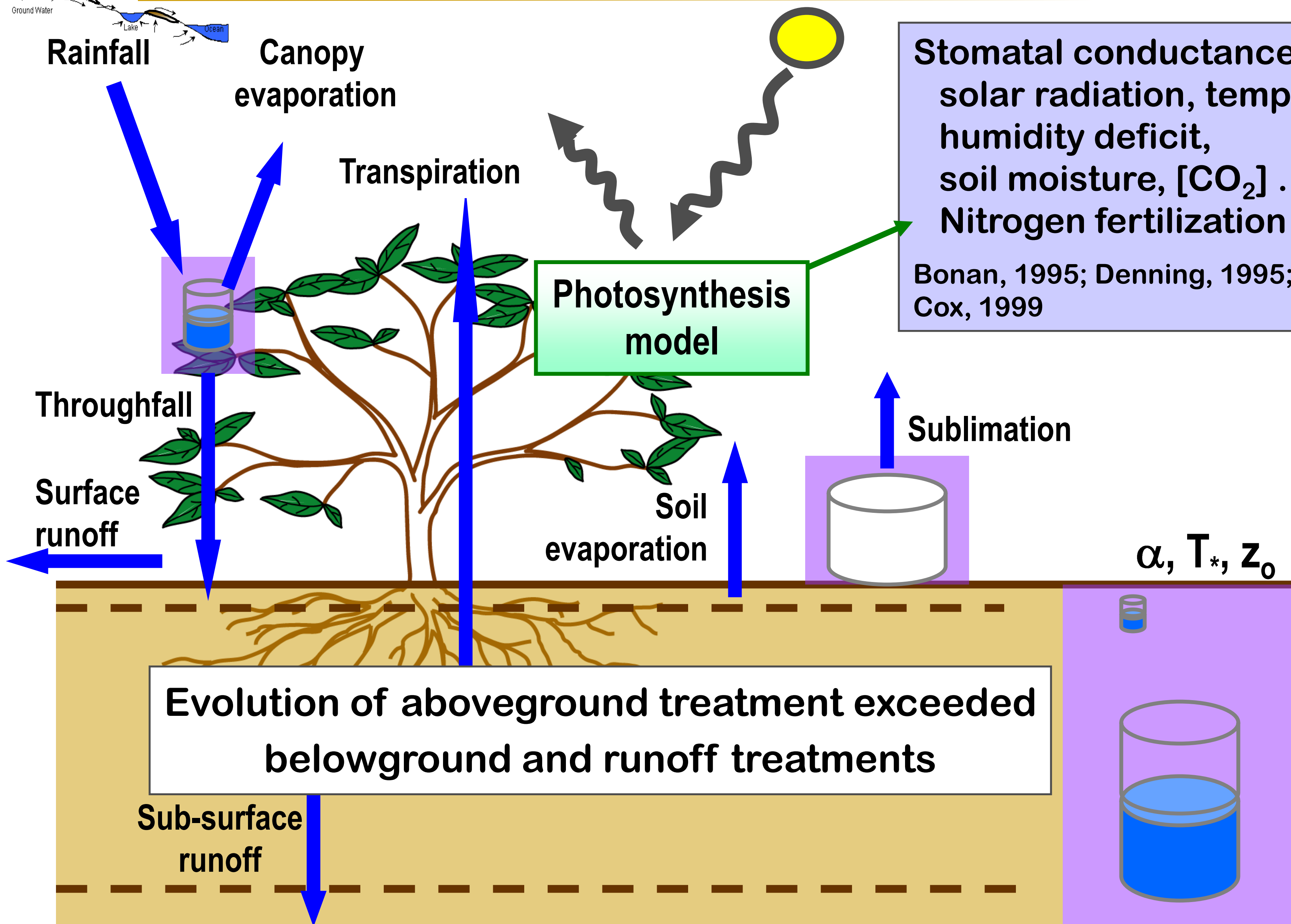
Figure courtesy G. Bonan

2nd Generation: Simple Canopy Models



- Dickinson et al., 1986
- Sellers et al., 1986

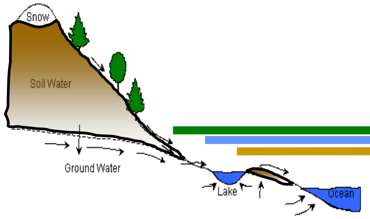
3rd Generation: Photosynthesis Model



Stomatal conductance:
solar radiation, temp,
humidity deficit,
soil moisture, $[CO_2]$ …
Nitrogen fertilization

Bonan, 1995; Denning, 1995; Cox, 1999

Evolution of aboveground treatment exceeded belowground and runoff treatments

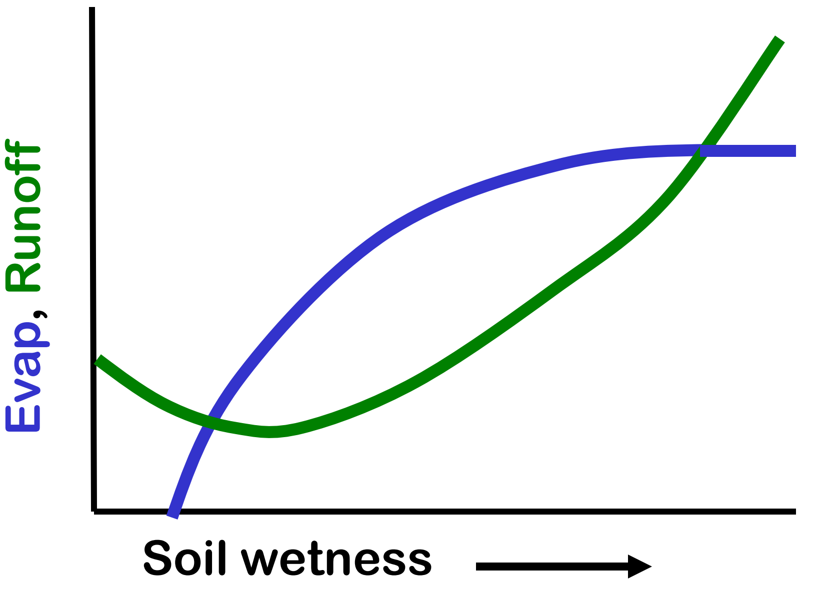


Modeling evaporation and runoff

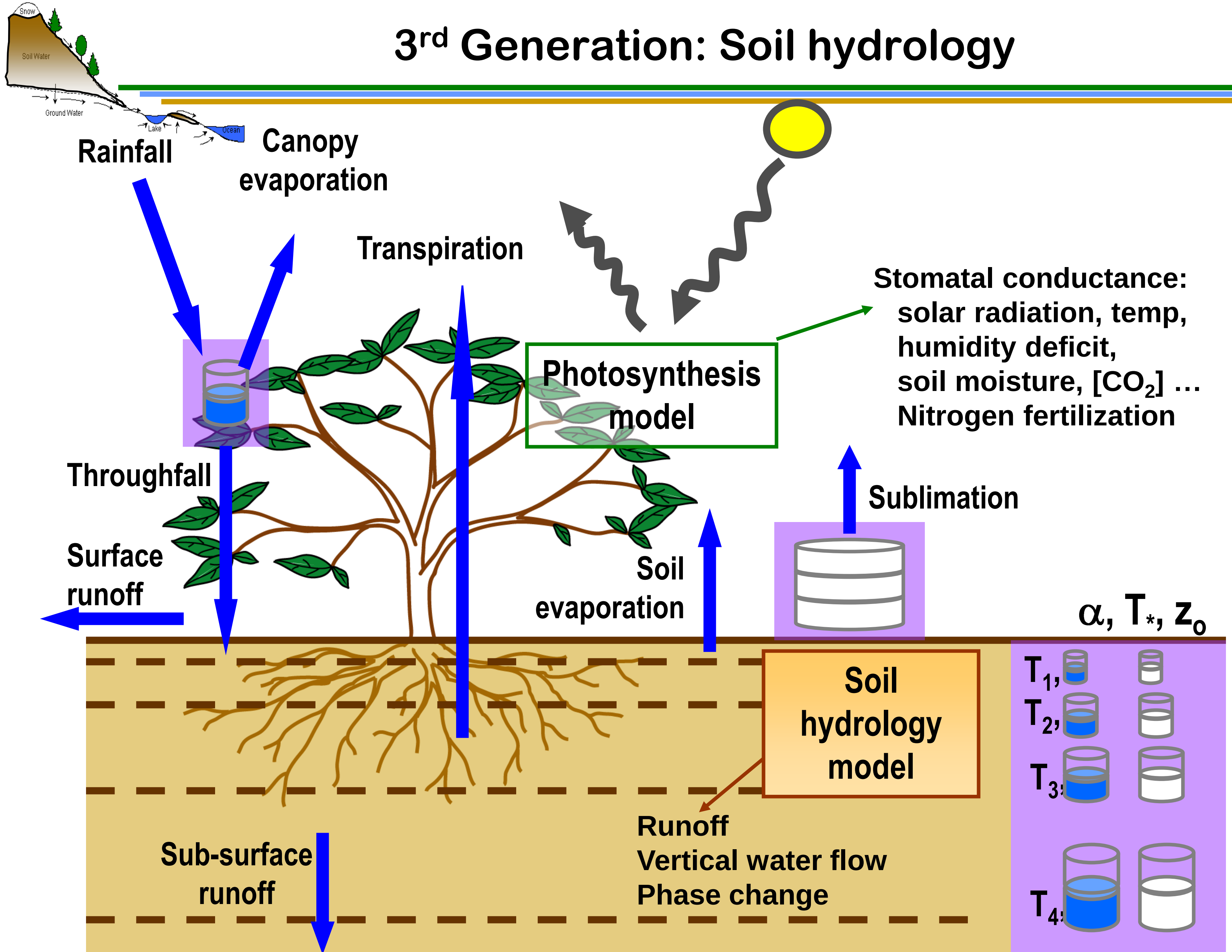
"The ability of a land-surface scheme to model evaporation correctly depends crucially on its ability to model runoff correctly. The two fluxes are intricately related."

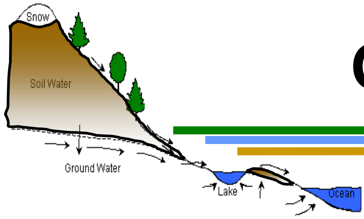
(Koster and Milly, 1997).

Runoff and evaporation vary non-linearly with soil moisture



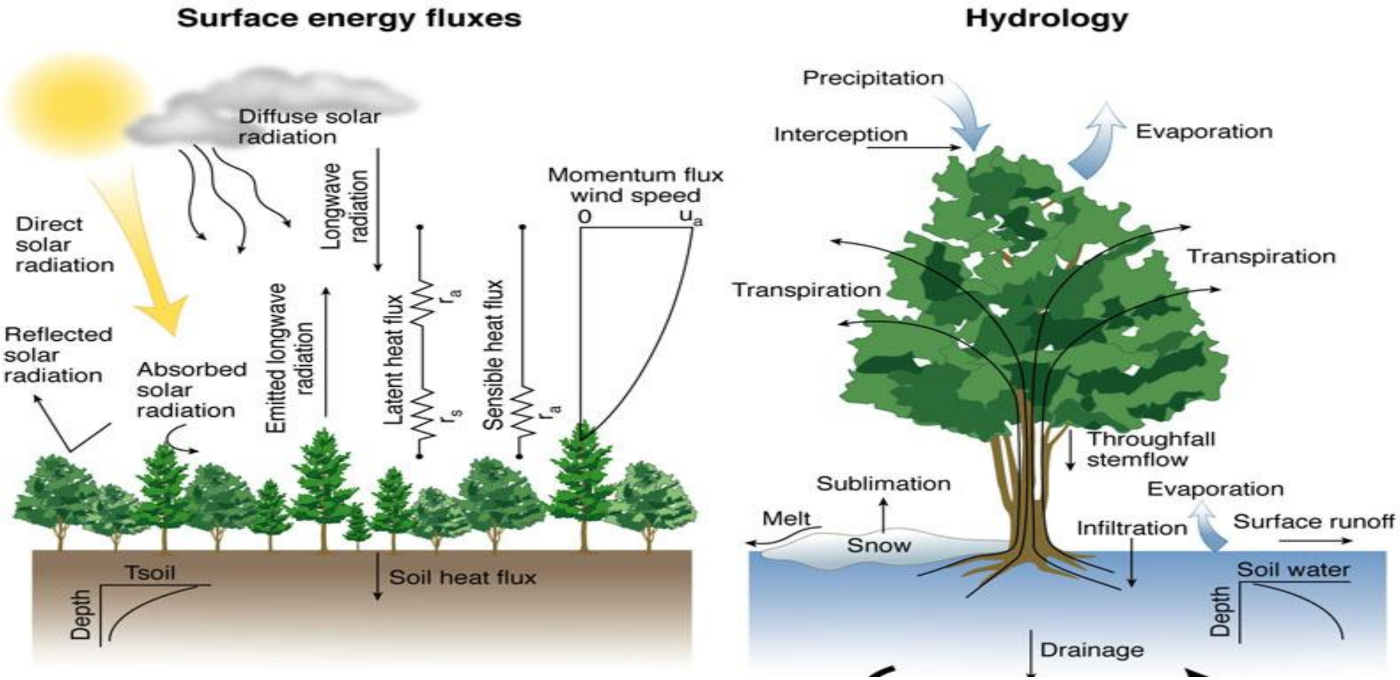
3^{rd} Generation: Soil hydrology



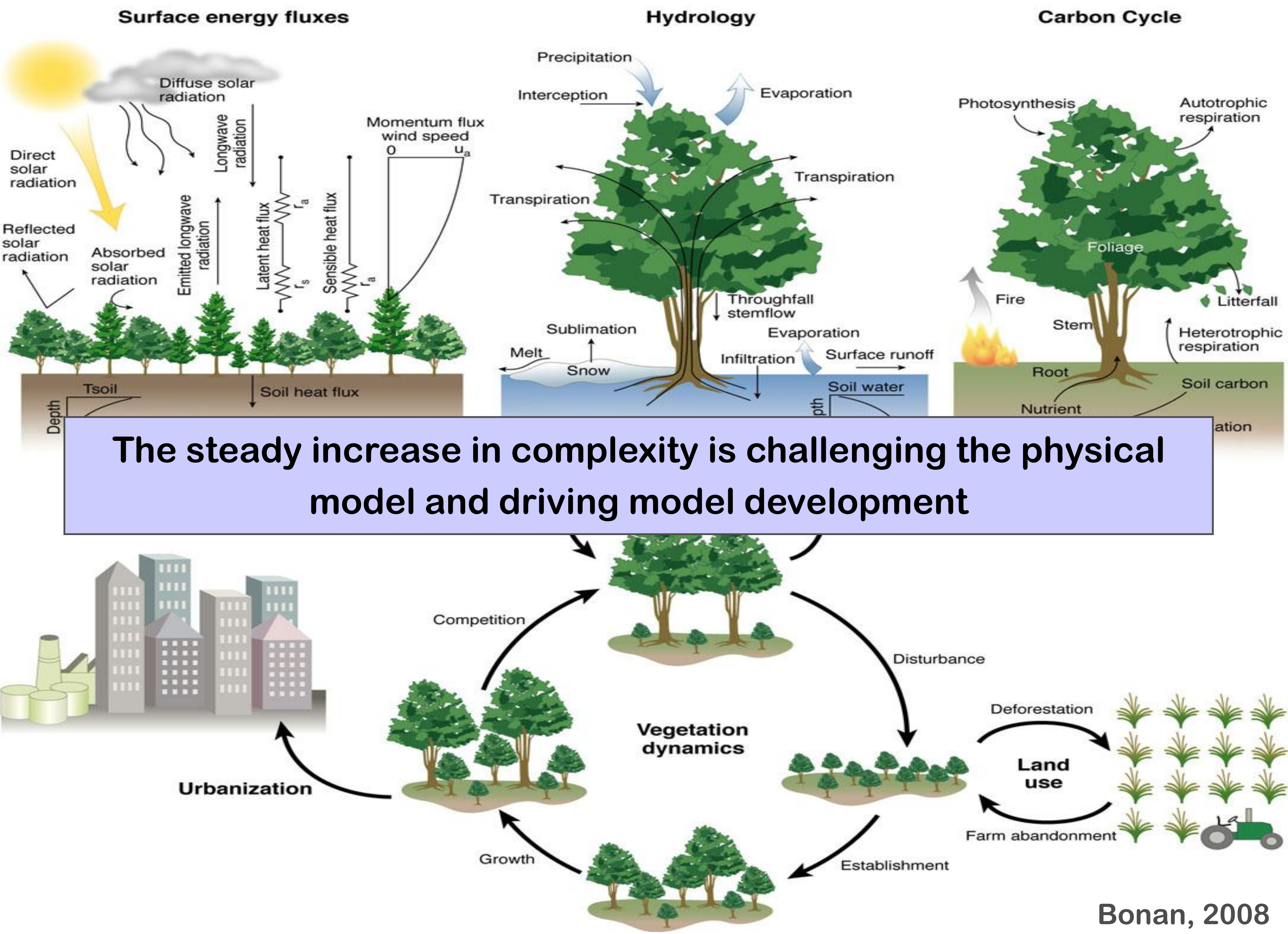


Origin of the Community Land Model (CLM)

- Concept of a community-developed land component for CCSM initially proposed at February 1996 LMWG meeting
- Initial development focused on evaluating best features of
  - LSM: NCAR land model
  - IAP94: Chinese Academy of Sciences land model
  - BATS: Biosphere-Atmosphere Transfer Scheme
- Effort led by Bob Dickinson, Gordon Bonan, Xubin Zeng, and Yongjiu Dai
- Subsequent model development CLM2 → CLM3 → CLM4 improved process representation combined with new functionality (e.g. DGVM, carbon cycle)

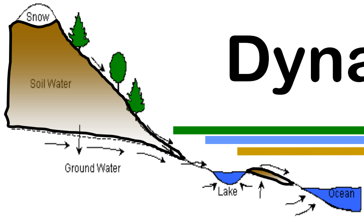

Surface energy fluxes
Diffuse solar radiation
Direct solar radiation
Longwave radiation
Momentum flux wind speed
0
u_a
Reflected solar radiation
Absorbed solar radiation
Emitted longwave radiation
Latent heat flux
r_a
r_s
Sensible heat flux
r_a
Tsoil
Depth
Soil heat flux
Hydrology
Precipitation
Interception
Evaporation
Transpiration
Transpiration
Throughfall stemflow
Sublimation
Evaporation
Melt
Snow
Infiltration
Surface runoff
Soil water
Depth
Drainage

Bonan, 2008



The steady increase in complexity is challenging the physical model and driving model development

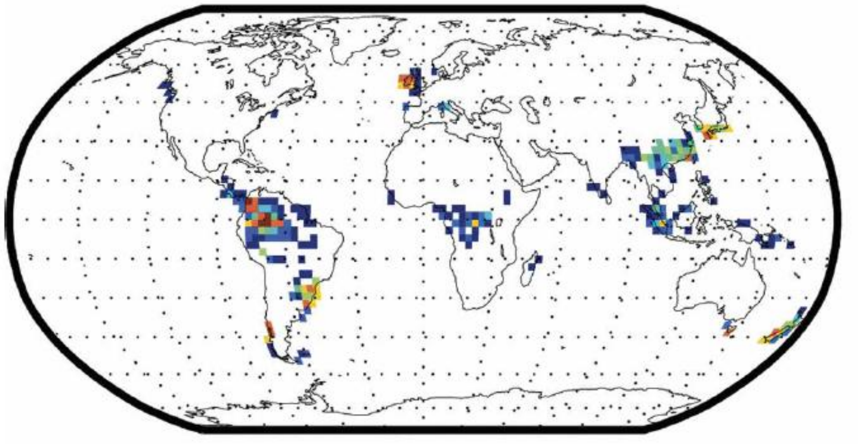
Bonan, 2008



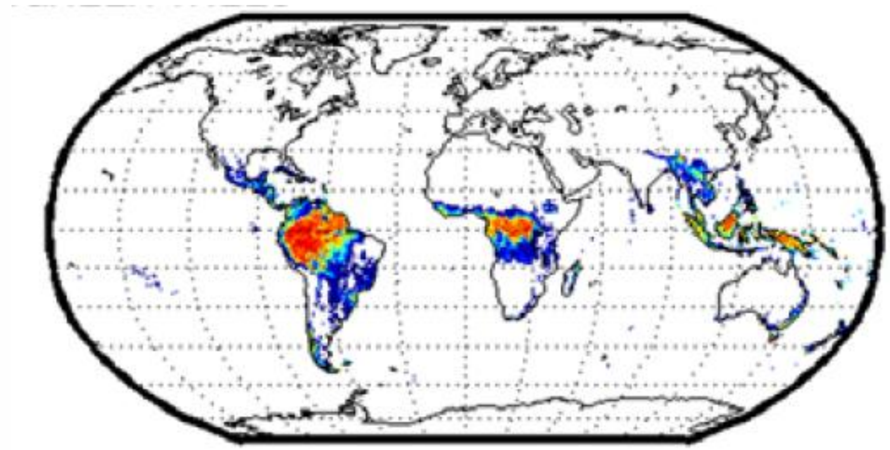
Dynamic Global Vegetation Model results with CLM3

Broadleaf evergreen tree

CLM 3.0

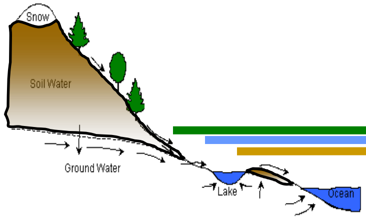


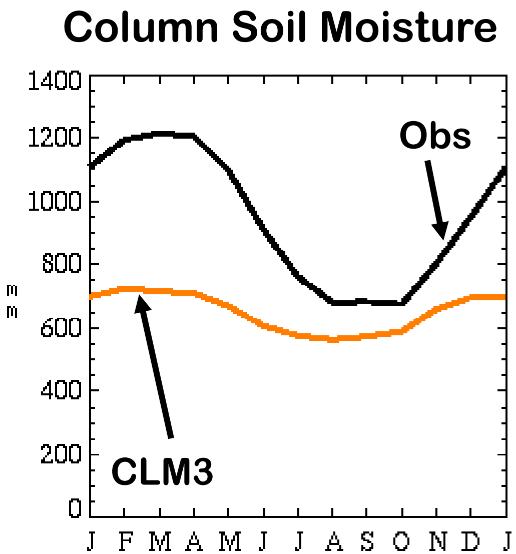
Obs

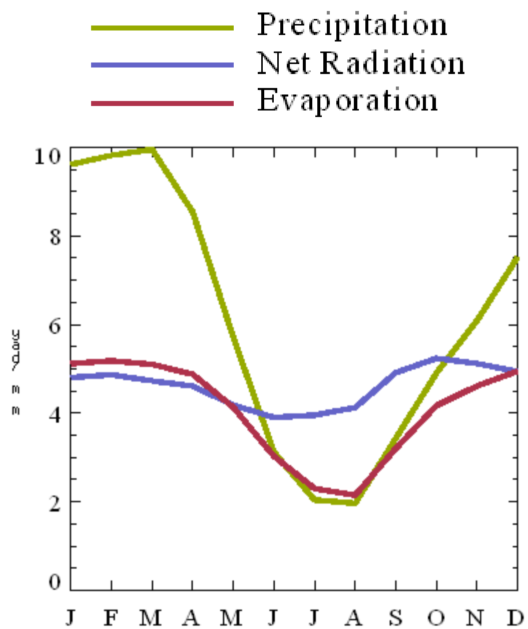


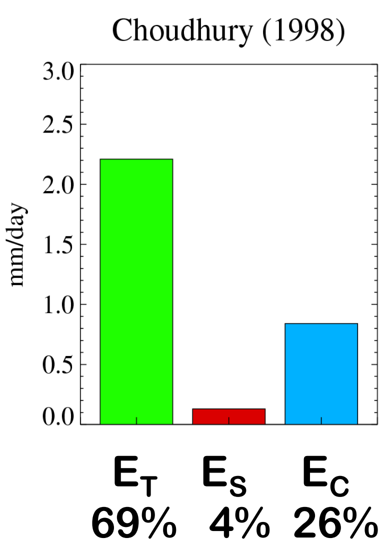
% Veg cover

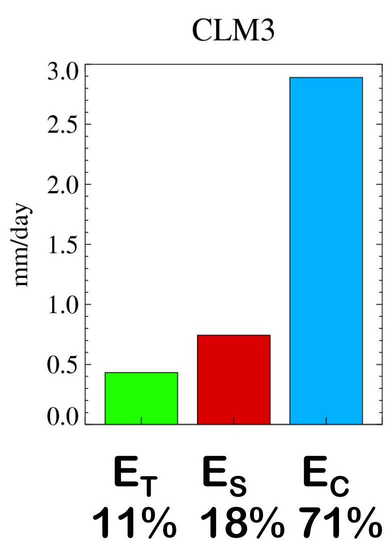
Amazonia hydrologic cycle Issues







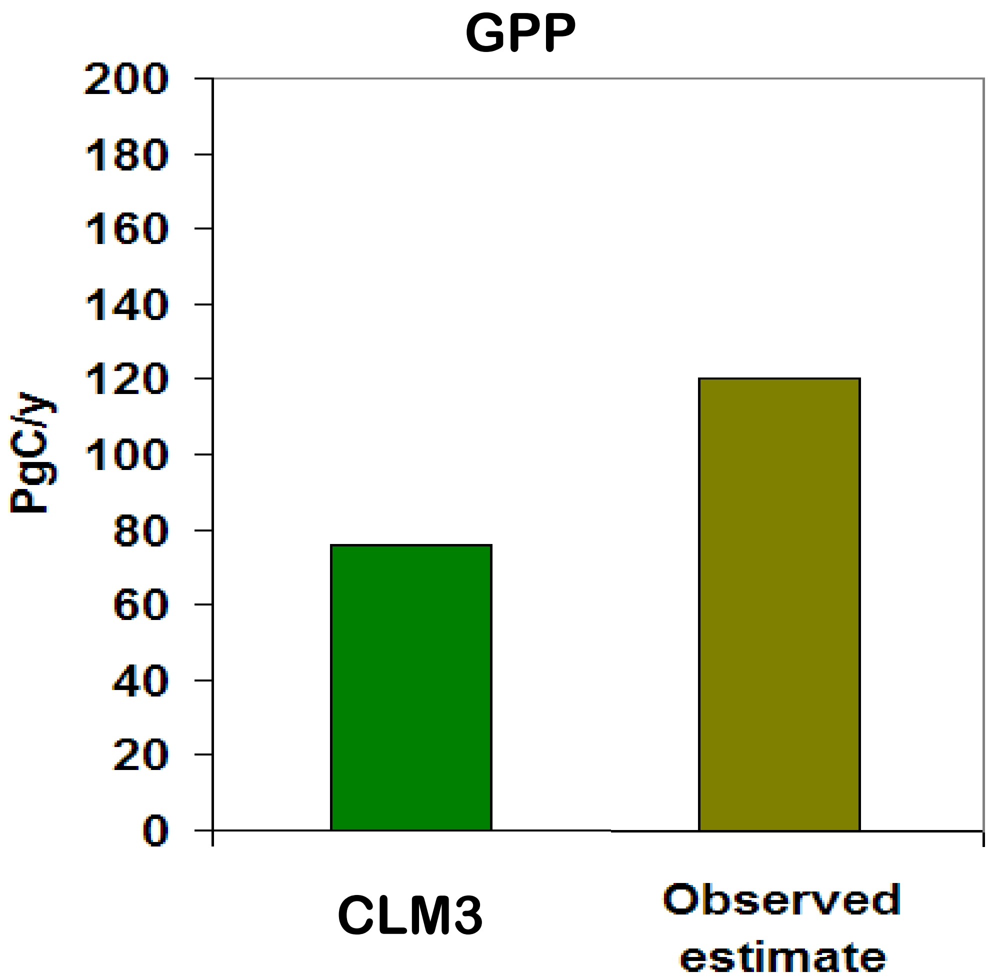




- Deep soil too dry, weak annual cycle of SM, no interseasonal SM storage
- Low evapotranspiration and high temperatures during dry season
- Low transpiration (photosynthesis); excessive canopy interception

Carbon cycle issues

Global gross primary productivity (GPP) is low in CLM3



Development of CLM3.5

- Deficiencies in CLM3 limiting CLM-CN and DGVM development
- CLM3.1 – interim version to get CN going
- First discussion at Spring 2005 LMWG meeting
- Gazillion iterations
- Released in May 2007
- Provide a platform for CLM4 development

NCAR
National Center for Atmospheric Research
Boulder, Colorado

Back to LMWG Diagnostics Package

CLM HYDROLOGY PROJECT

Disclaimer: These model results are from preliminary lmwg clm hydrology pr … buted.

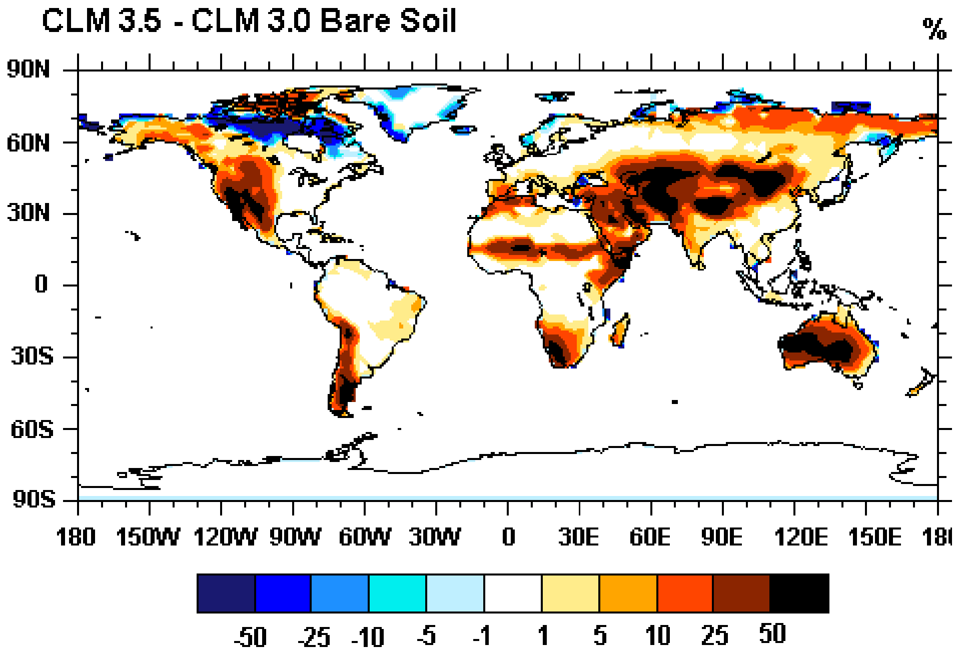
2005 CCSM Workshop

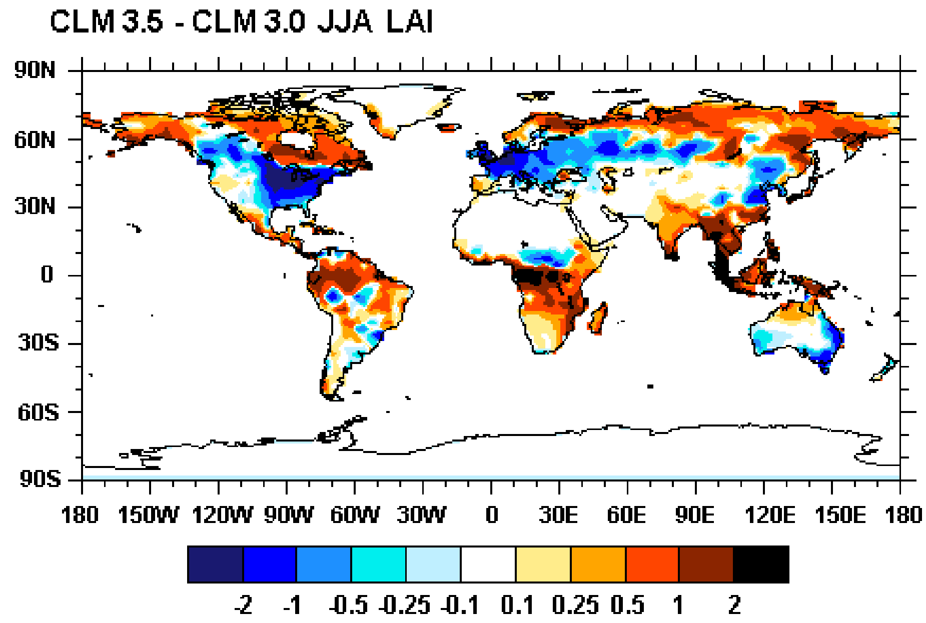
Keith Oleson's LMWG presentation

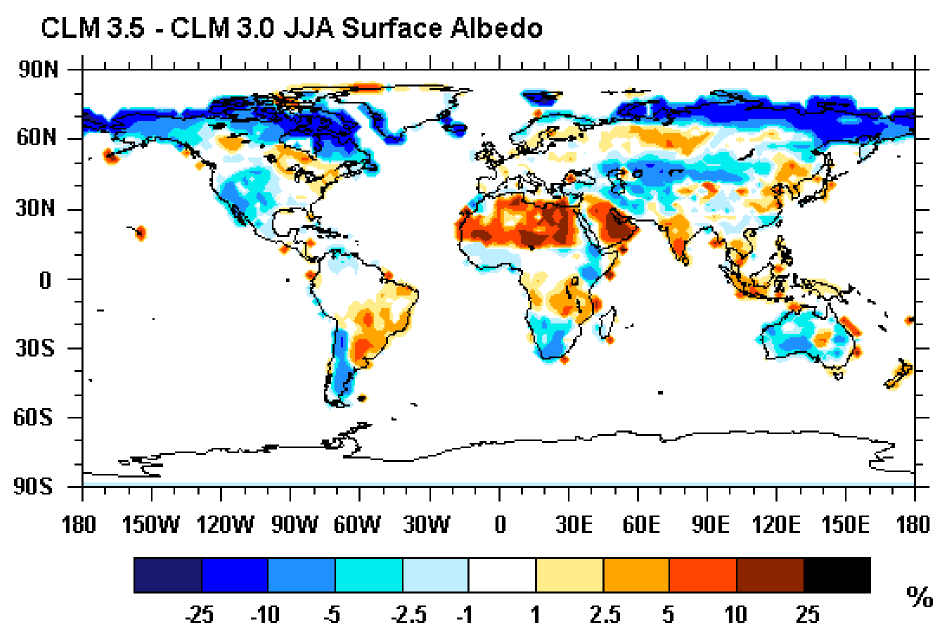
CLM Offline Simulation Descriptions

- hyd_off_con3 (CAM3/CLM3 release code, started in 1948)
- hydp2_off_commun_hk15 (community hydrology, started in 1979)
- hydp2_off_commun_hk16 (community hydrology, started in 1948)
- hydp2_off_commun_hk19 (same as hk15 but with snowage fix)
- hydp2_off_commun_hk20 (same as hk16 but with water balance fix)
- hydp2_off_commun_hk21 (same as hk16 but with equilibrium water table
- hydp2_off_commun_hk22 (same as hk16 but initialized from hk21)
- hydp2_off_commun_hk23 (same as hk16 but with D. Lawrence s_node fix
- hydp2_off_commun_hk25 (same as hk16 but with G.-Y. Niu s_node fix)
- hydp2_off_commun_hk26 (same as hk23 but with changes to qcharge and
- hydp2_off_commun_hk27 (same as hk26 but with equilibrium water table
- hydp2_off_commun_hk28 (same as hk26 but initialized from end of hk27)
- hydp2_off_commun_hk29 (same as hk26 but with repeated 1948 forcing)
- hydp2_off_commun_hk16tag (same as hk16 but using tagged code (clm3_
- hydp2_off_commun_hk26tag (same as hk26 but using tagged code (clm3_
- hydp2_off_commun_hk26fl_2 (same as hk26 but with f=1.2)
- hydp2_off_commun_hk26tagf (same as hk26tag but with final surface data
- hydp2_off_commun_expa85 (same as hk26tagf but with water balance err … tag 85).
- hydp2_off_commun_hk30 (same as hk26 but with new smpso/smpsc value
- hydp2_off_commun_hk32 (same as hk26 but with subgrid precip fix (includes T. Qian precip frequency adjustment)
- hydp2_off_commun_hk33 (same as hk26 but with 0.35 interception factor)
- hydp2_off_commun_hk34 (same as hk26 but with %clay reduced by 80%)
- hydp2_off_commun_hk35 (same as hk26 but with ws fix and repeated 1948 forcing)
- hydp2_off_commun_hk36 (same as hk26 but with ws fix and equilibrium water table spinup equations)
- hydp2_off_commun_hk37 (same as hk28 but with ws fix and initialized from end of hk36)
- hydp2_off_commun_expa89 (thru tag expa_89)
- hydp2_off_commun_hk38 (same as expa89 but with PT's btran)
- hydp2_off_commun_hk39 (same as hk38 but with PT's nitrogen limitation)
- hydp2_off_commun_hk40 (same as hk39 but with tfrz changes)

New Surface Dataset; CLM 3.5 (MODIS) – CLM 3.0

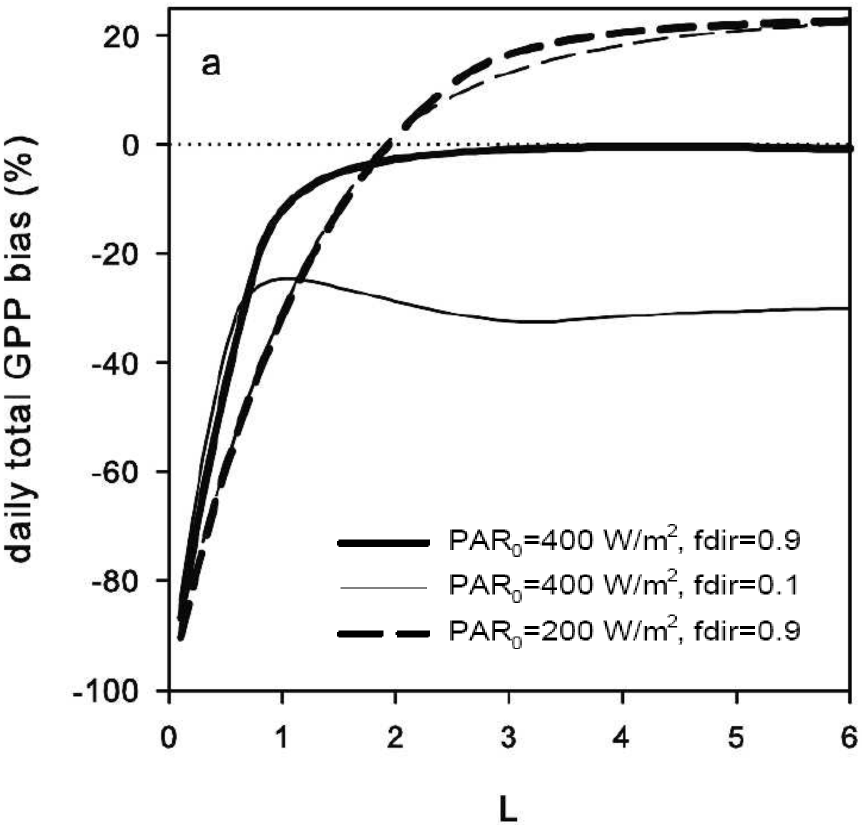






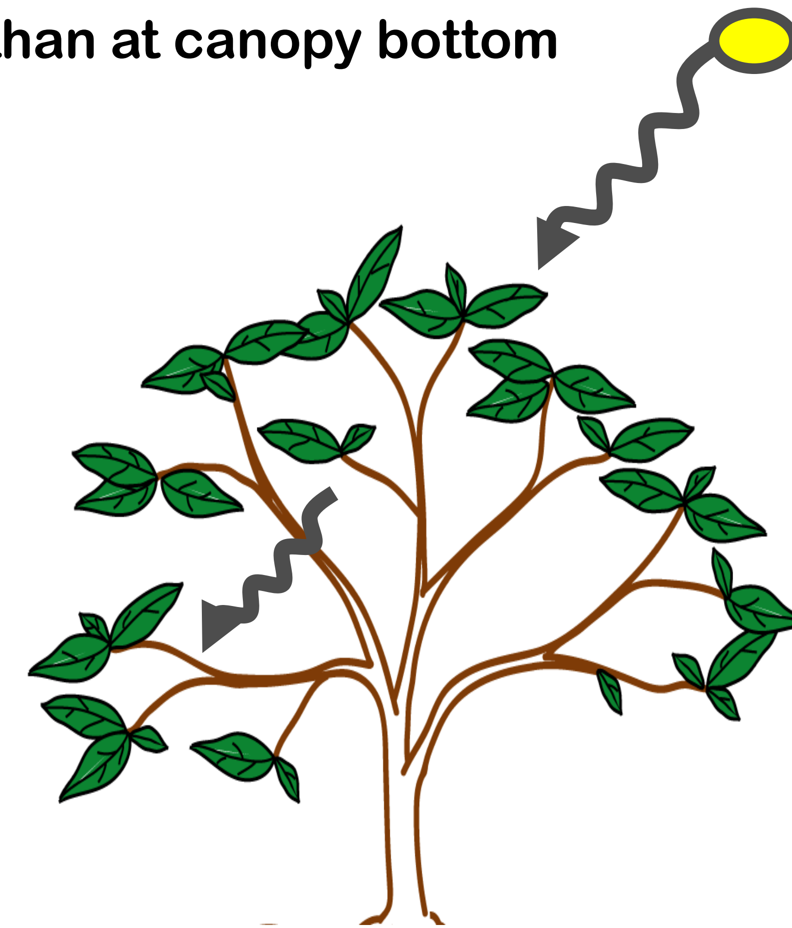
1. Large increase in bare soils
2. Increase in LAI for tropical forests
3. Decrease in summer and increase in winter LAI for savannas and grasslands
4. higher albedo for Sahara and Arabian peninsula; lower albedo for Arctic tundra

Improved canopy integration scheme



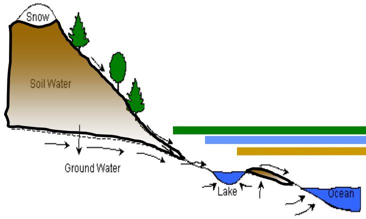
Two-leaf (sunlit/shaded) model

Leaves at canopy top are thicker than at canopy bottom



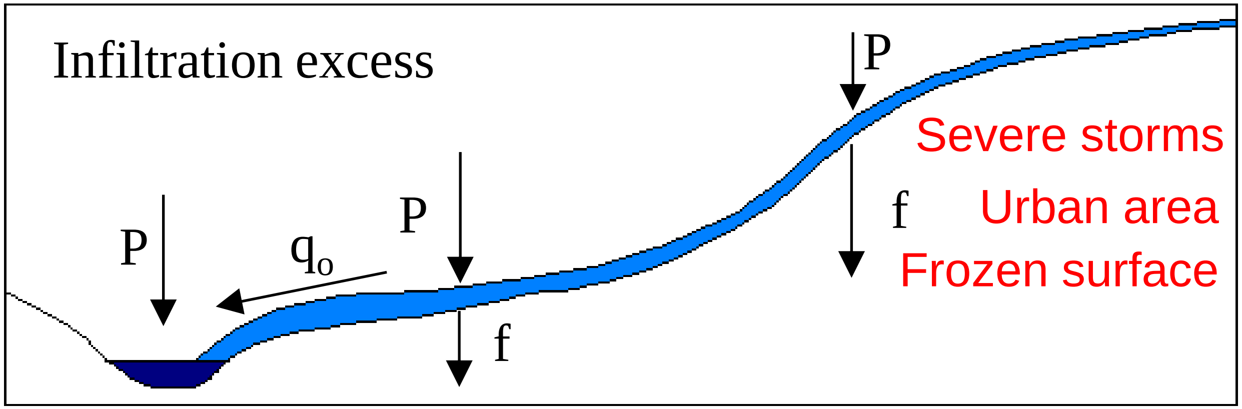
Improves GPP and transpiration, but dries already dry soils even further

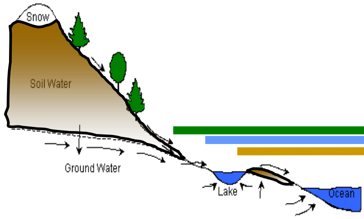
Thornton and Zimmerman, 2007



Runoff processes

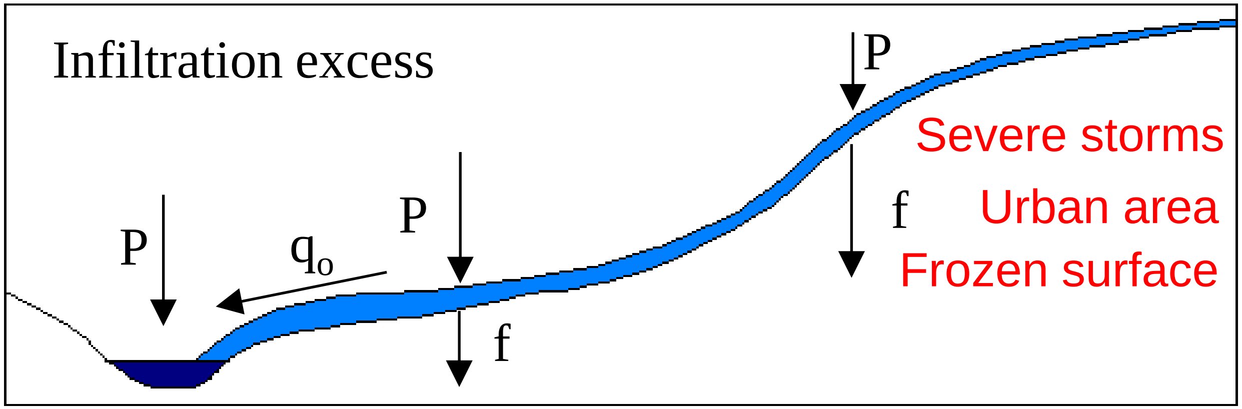
SIMTOP: TOPMODEL-based runoff

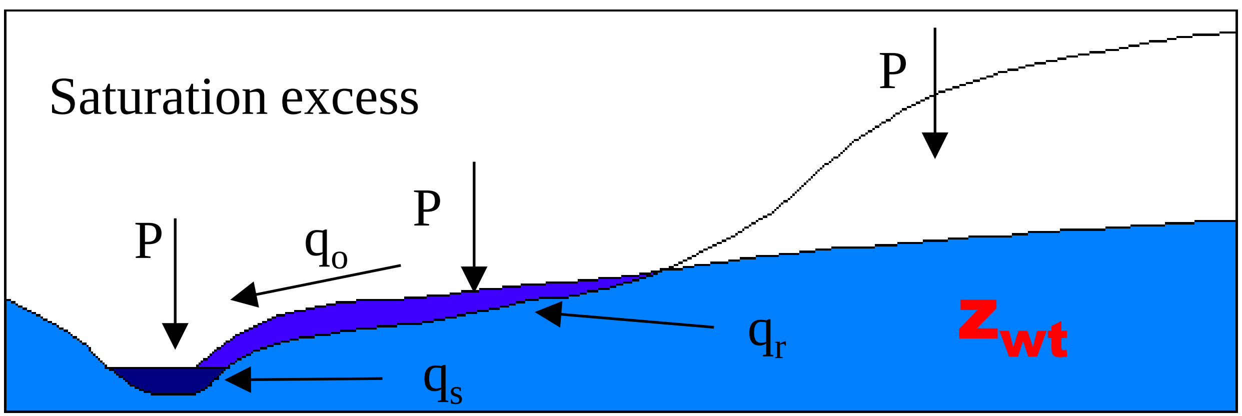


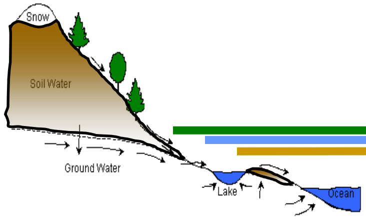


Subgrid-scale soil moisture heterogeneity

SIMTOP: TOPMODEL-based runoff



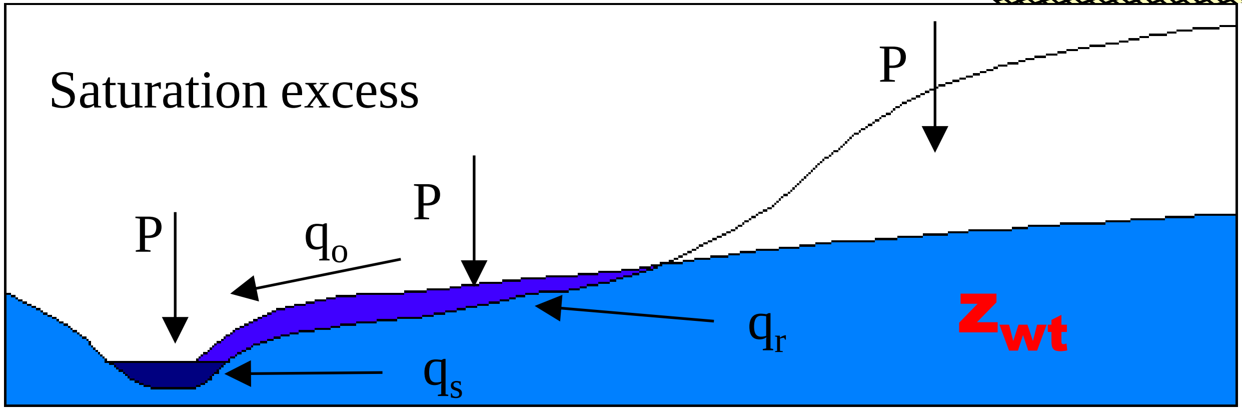


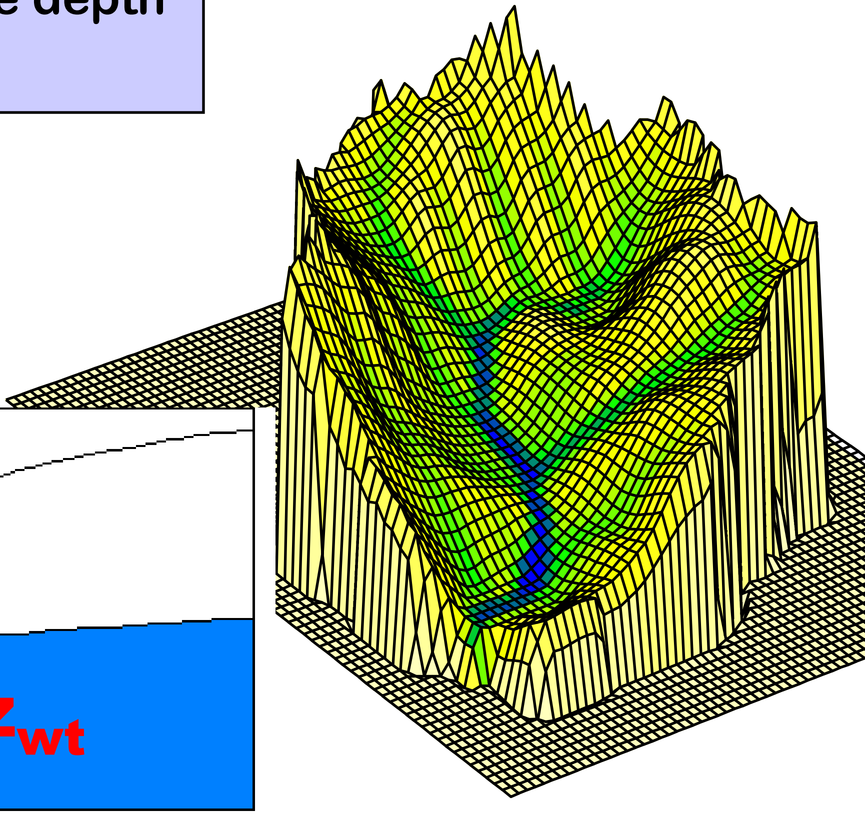


Subgrid-scale soil moisture heterogeneity

SIMTOP: TOPMODEL-based runoff

Saturated fraction: function of water table depth and topography



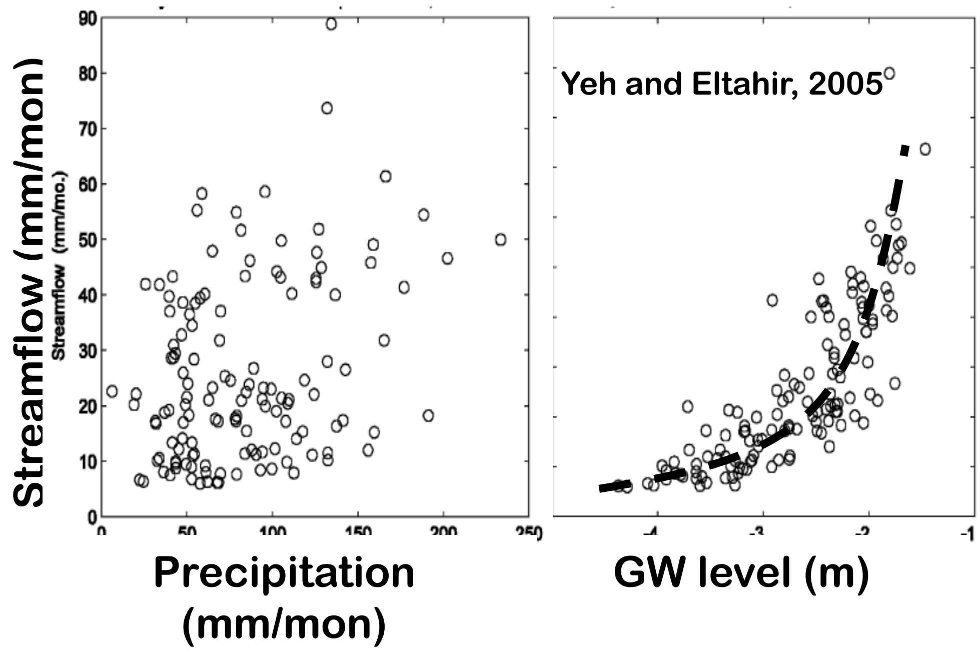


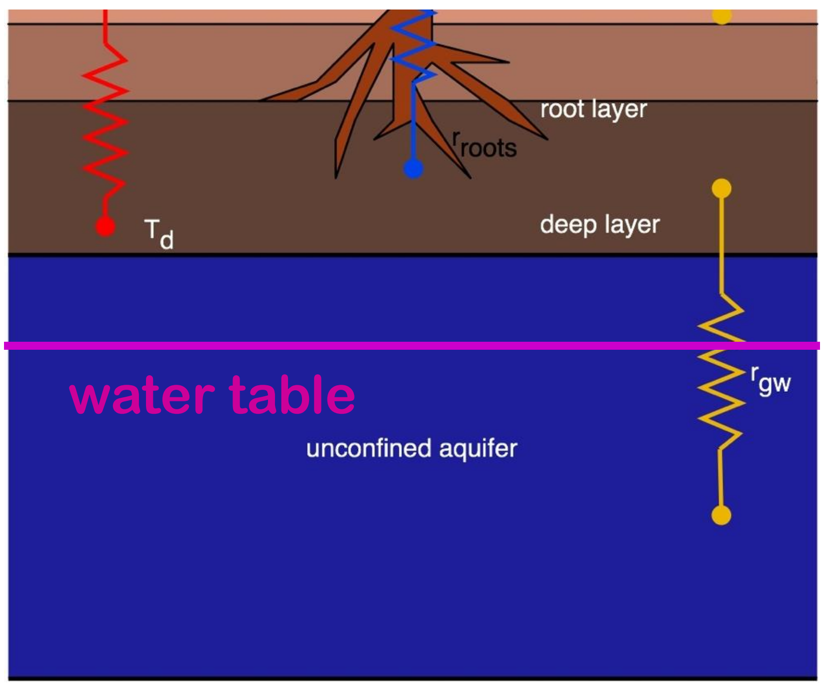
Niu and Yang, 2005

Groundwater in the climate system

Groundwater controls runoff (Yeh and Eltahir, 2005)

Groundwater affects soil moisture and ET (Gutowski et al, 2002; York et al., 2002)

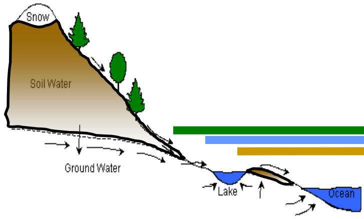




Groundwater model (SIMGM) determines water table depth

Subsurface runoff is exponential function of water table depth

Niu and Yang, 2005



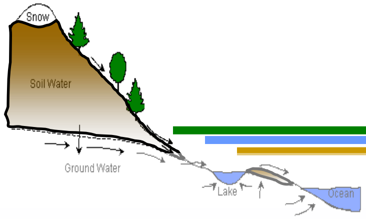
CLM3 → CLM3.5

Modifications to soil hydrology

- Adopt SIMTOP (TOPMODEL-based surface runoff)
- Adopt SIMGM (groundwater model)
- New frozen soil scheme (freezing point depression, permeability of icy soil)
- Added soil evaporation resistance term that is function of soil moisture

Modifications to biophysics

- Revised canopy integration including 2-leaf (sunlit/shade) model
- New surface dataset (PFTs, LAI) based on MODIS data
- Canopy interception scaling
- Effective nitrogen limitation
- Added PFT-dependency to soil moisture stress function
- Permit root water uptake from mixed liquid/ice layers



CLM3.5 in print

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, G01021, doi:10.1029/2007JG000563, 2008

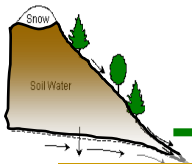
Improvements to the Community Land Model and their impact on the hydrological cycle

K. W. Oleson,[1] G.-Y. Niu,[2] Z.-L. Yang,[2] D. M. Lawrence,[1] P. E. Thornton,[1] P. J. Lawrence,[3] R. Stöckli,[4,5,6] R. E. Dickinson,[7] G. B. Bonan,[1] S. Levis,[1] A. Dai,[1] and T. Qian[1]

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, G01025, doi:10.1029/2007JG000562, 2008

Use of FLUXNET in the Community Land Model development

R. Stöckli,[1,2,3] D. M. Lawrence,[4] G.-Y. Niu,[5] K. W. Oleson,[4] P. E. Thornton,[4] Z.-L. Yang,[5] G. B. Bonan,[4] A. S. Denning,[1] and S. W. Running[6]



CLM3.5: Foundation papers

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, D07103, doi:10.1029/2006JD007522, 2007

Development of a simple groundwater model for use in climate models and evaluation with Gravity Recovery and Climate Experiment data

Guo-Yue Niu,[1] Zong-Liang Yang,[1] Robert E. Dickinson,[2] Lindsey E. Gulden,[1] and Hua Su[1]

JOURNAL OF CLIMATE

An Improved Canopy Integration Scheme for a Land Surface Model with Prognostic Canopy Structure

PETER E. THORNTON NIKLAUS E. ZIMMERMANN

JOURNAL OF HYDROMETEOROLOGY

Effects of Frozen Soil on Snowmelt Runoff and Soil Water Storage at a Continental Scale

GUO-YUE NIU AND ZONG-LIANG YANG

JOURNAL OF HYDROMETEOROLOGY

The Partitioning of Evapotranspiration into Transpiration, Soil Evaporation, and Canopy Evaporation in a GCM: Impacts on Land–Atmosphere Interaction

DAVID M. LAWRENCE, PETER E. THORNTON, KEITH W. OLESON, AND GORDON B. BONAN

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, G01023, doi:10.1029/2006JG000168, 2007

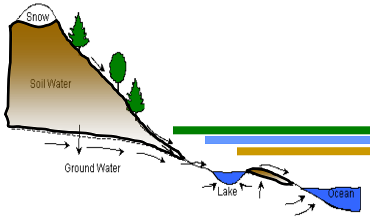
Representing a new MODIS consistent land surface in the Community Land Model (CLM 3.0)

Peter J. Lawrence[1] and Thomas N. Chase[1]

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 110, D21106, doi:10.1029/2005JD006111, 2005

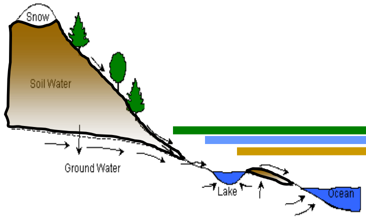
A simple TOPMODEL-based runoff parameterization (SIMTOP) for use in global climate models

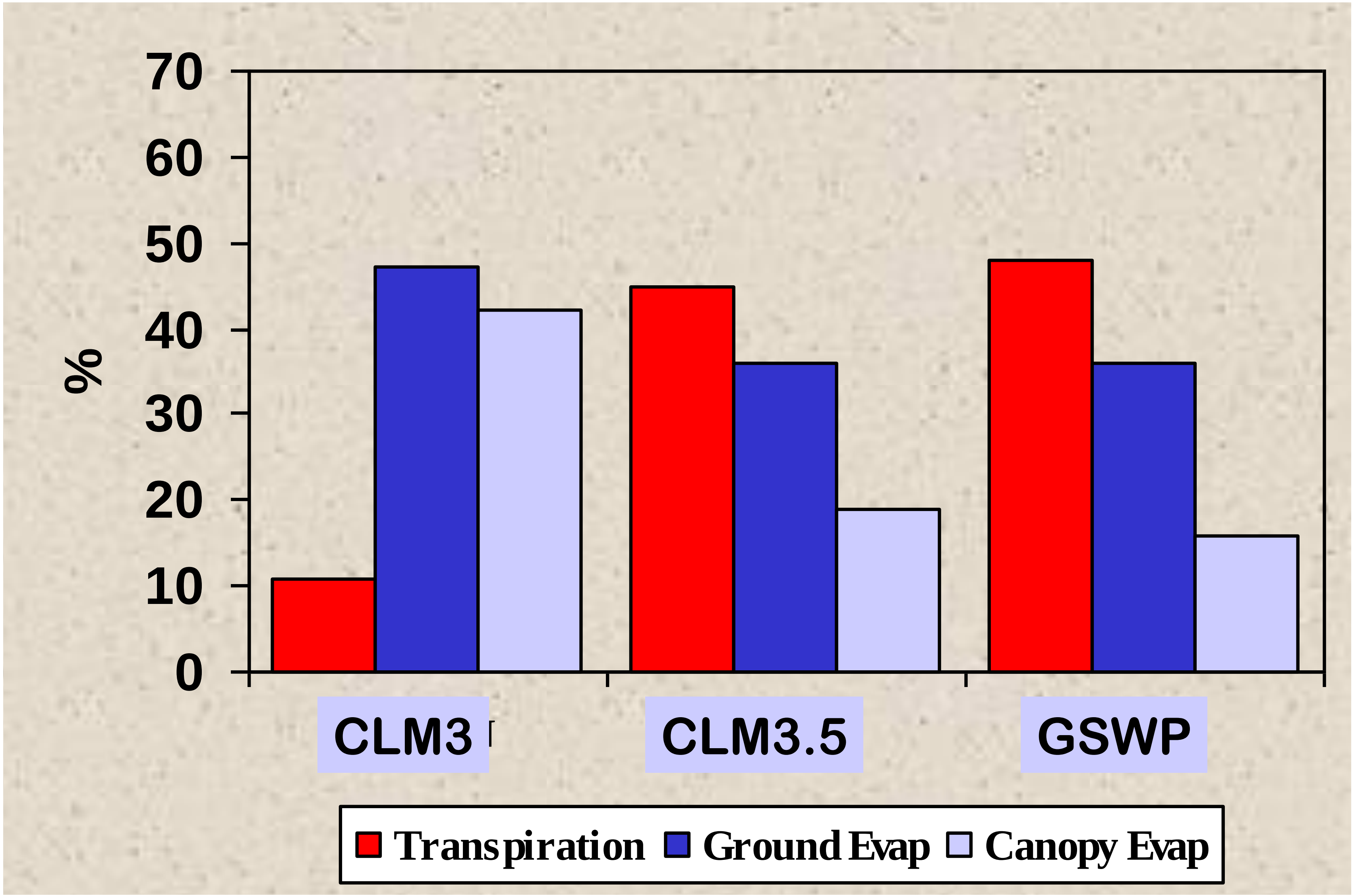
Guo-Yue Niu and Zong-Liang Yang Robert E. Dickinson Lindsey E. Gulden



Results

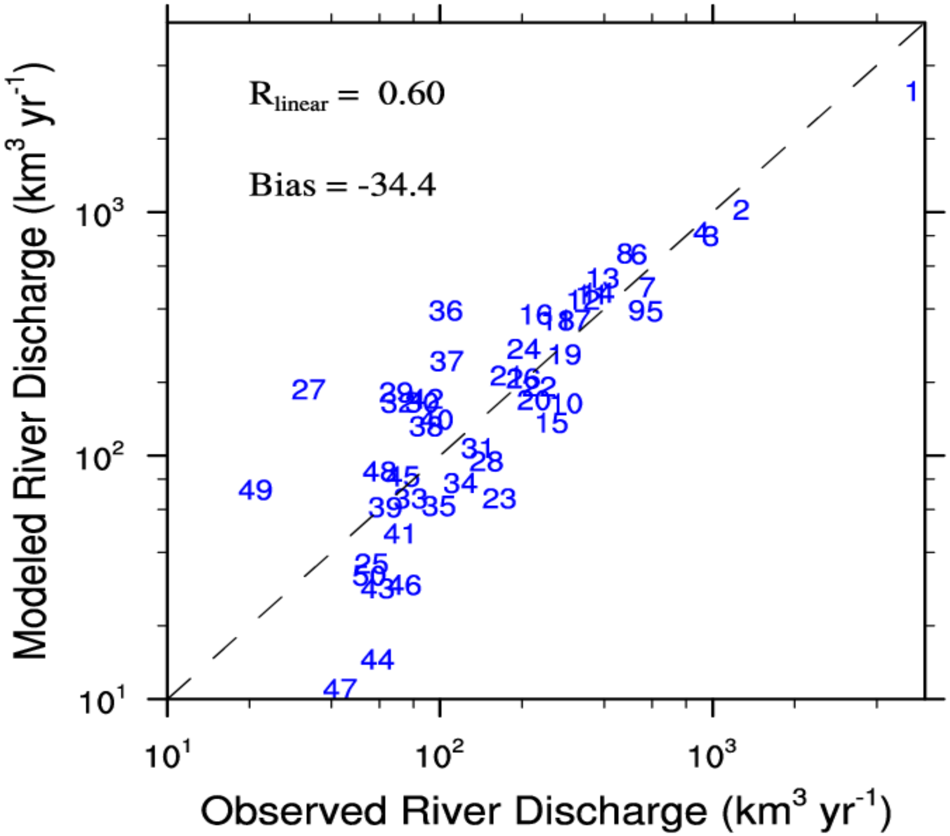
Global Partitioning of Evapotranspiration



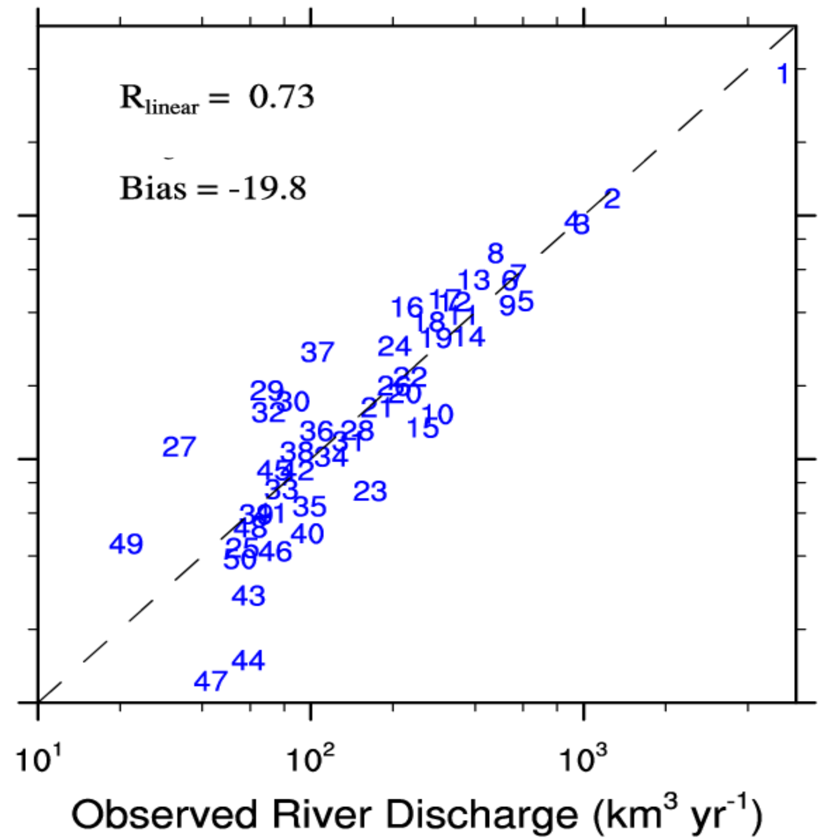


River discharge (minor improvement)

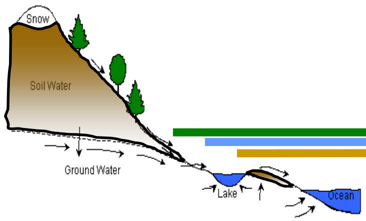
CLM3



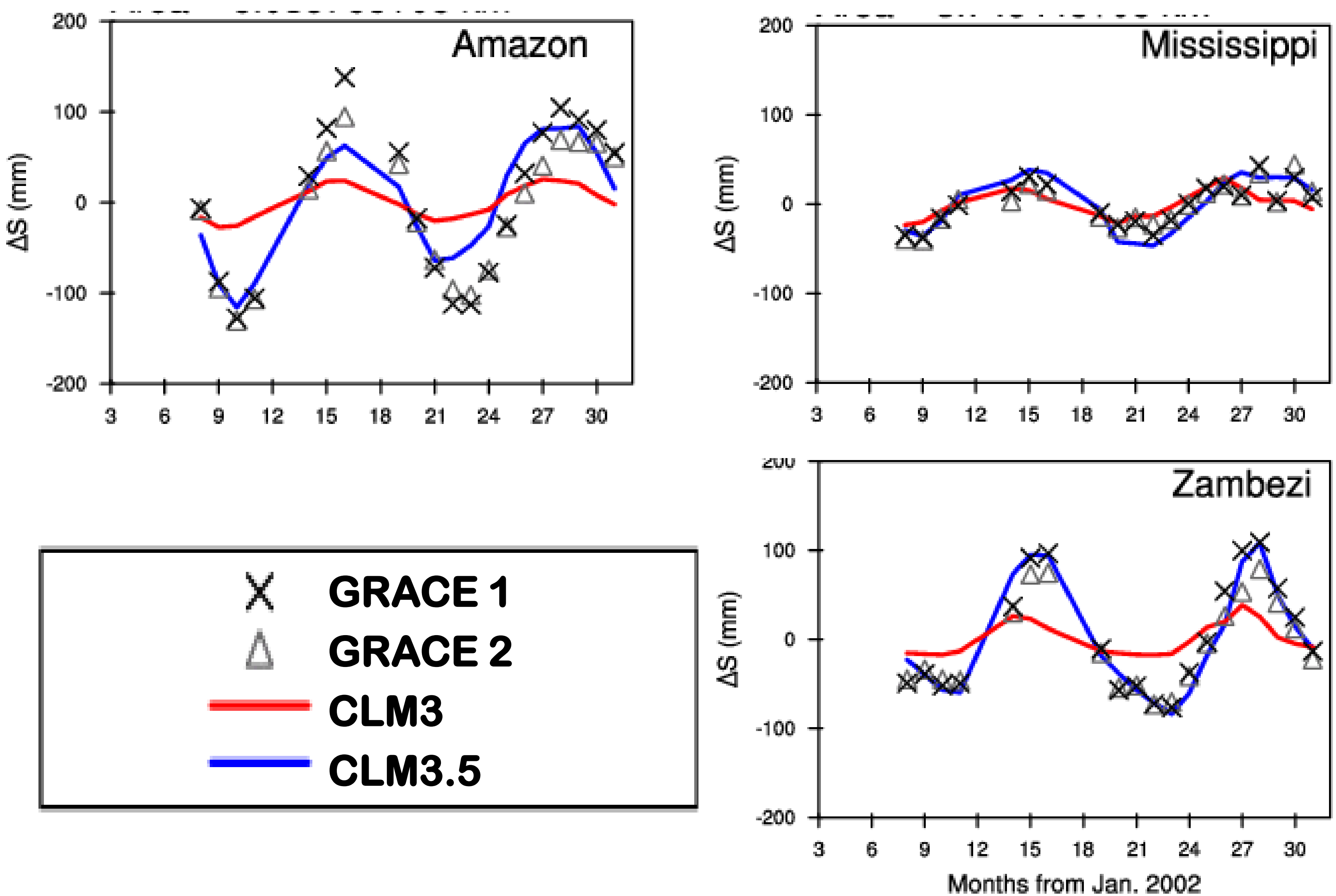
CLM3.5



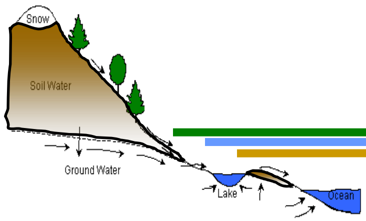
Phase of runoff annual cycle generally improved



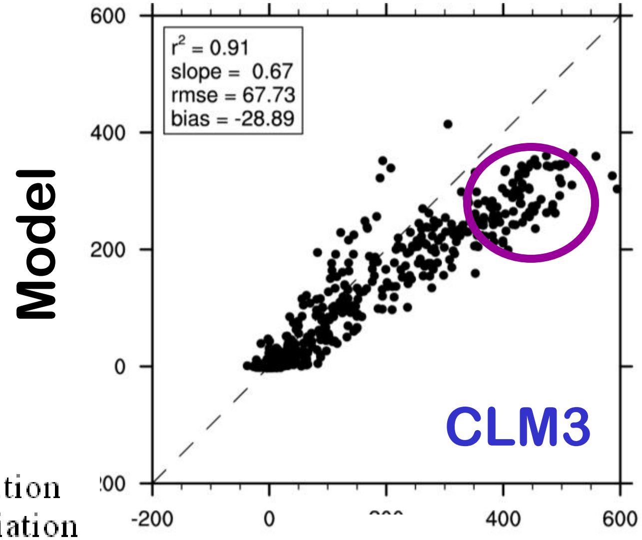
Water storage



Abracos tower site (Amazon)

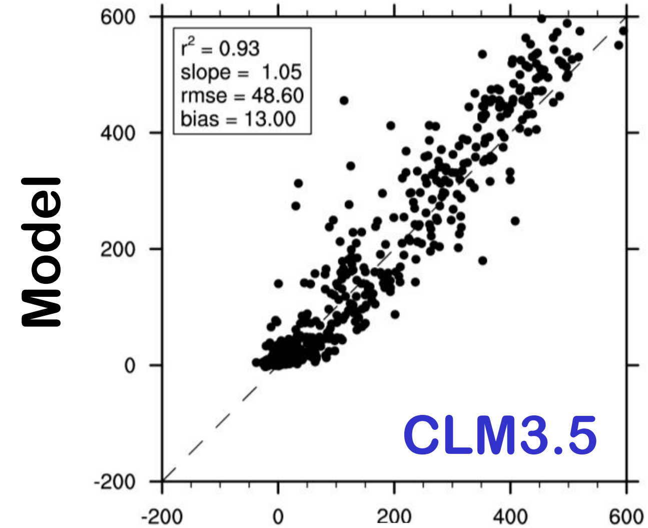


Latent Heat Flux

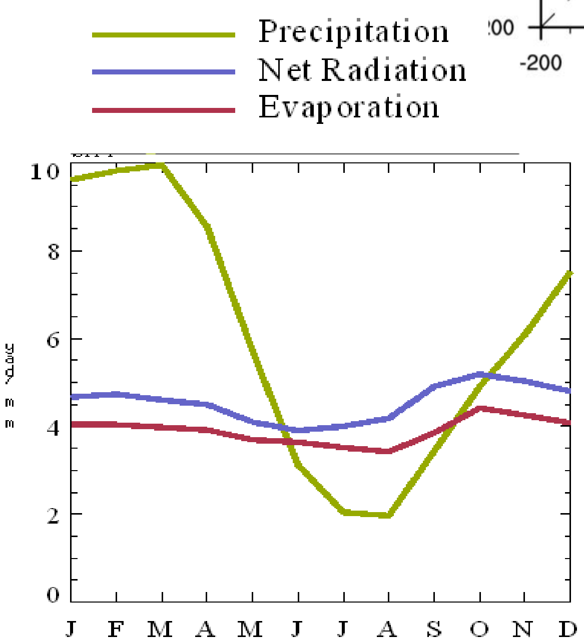


OBS

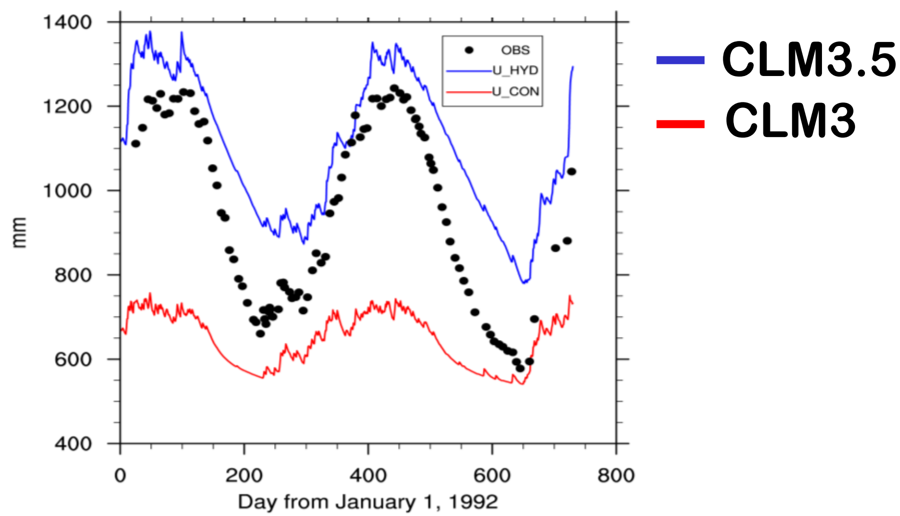
Latent Heat Flux



OBS



Total soil water



Observations: FLUXNET, a global network

USED SITES IN OUR STUDY:

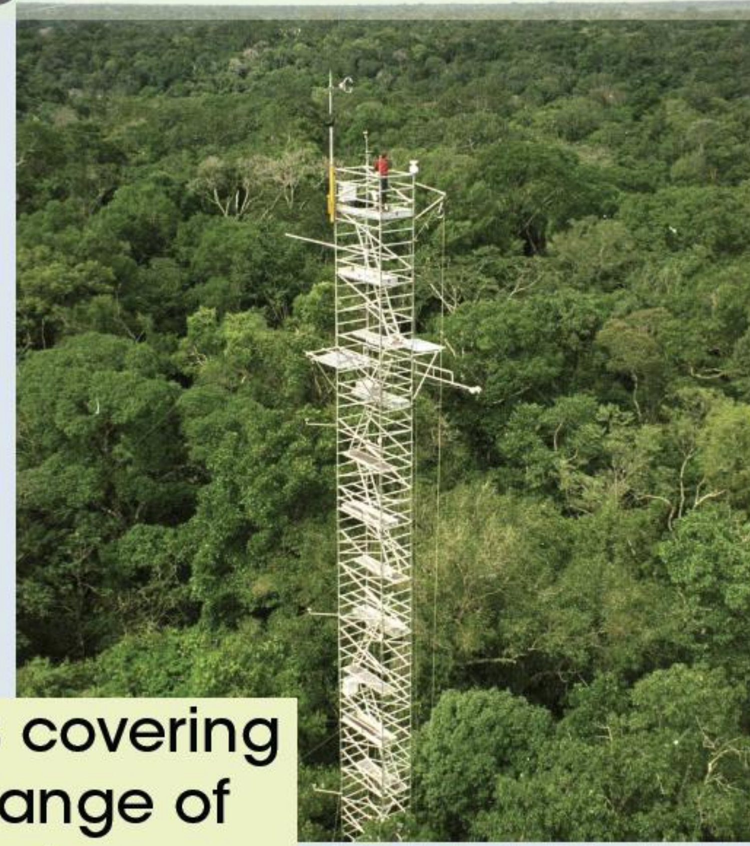
- Morgan Monroe (1999-2005)
- Fort Peck (2000-2005)
- Harvard Forest (1994-2003)
- Niwot Ridge (1999-2004)
- Boreas (1994-2005)
- Lethbridge (1998-2004)

- Santarem KM83 (2001-2003)
- Tapajos KM67 (2002-2005)

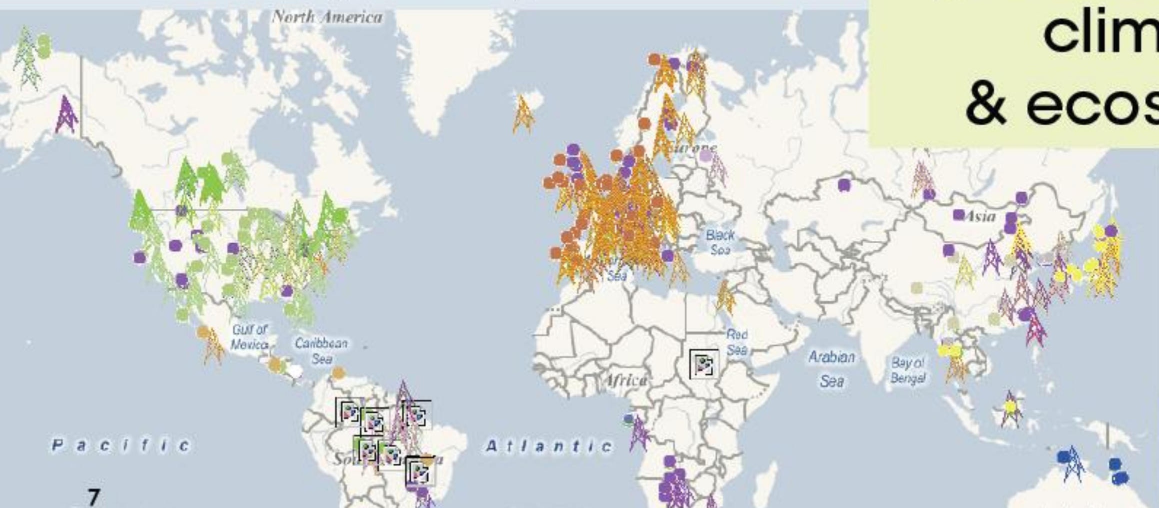
- Castelporziano (2000-2005)
- Collelongo (1999-2003)
- El Saler (1999-2005)
- Kaamanen (2000-2005)
- Hyytiälä (1997-2005)
- Tharandt (1998-2003)
- Vielsalm (1997-2005)

Color Legend:

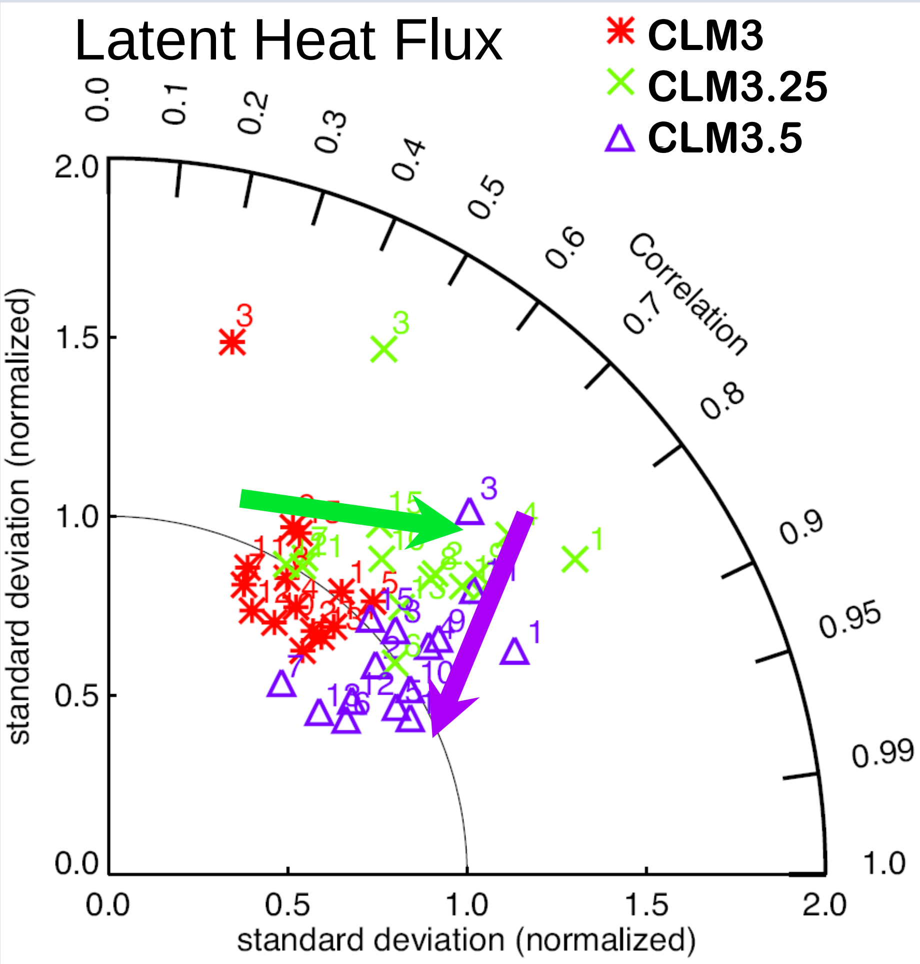
temperate
tropical
boreal
sub-alpine
north-boreal
mediterranean

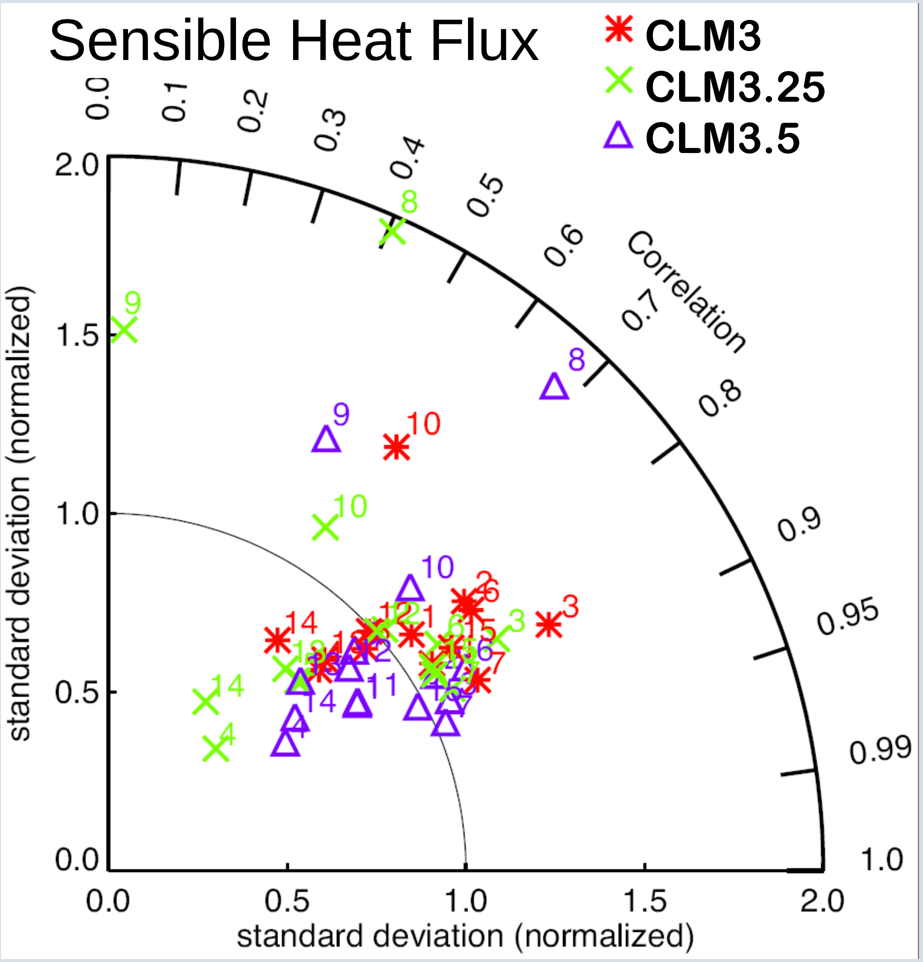


300+ sites covering global range of climates & ecosystems

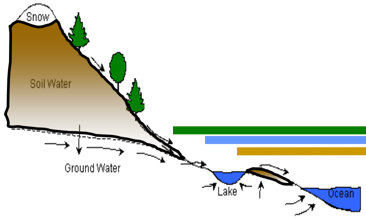


Summary of Results: all tower flux sites





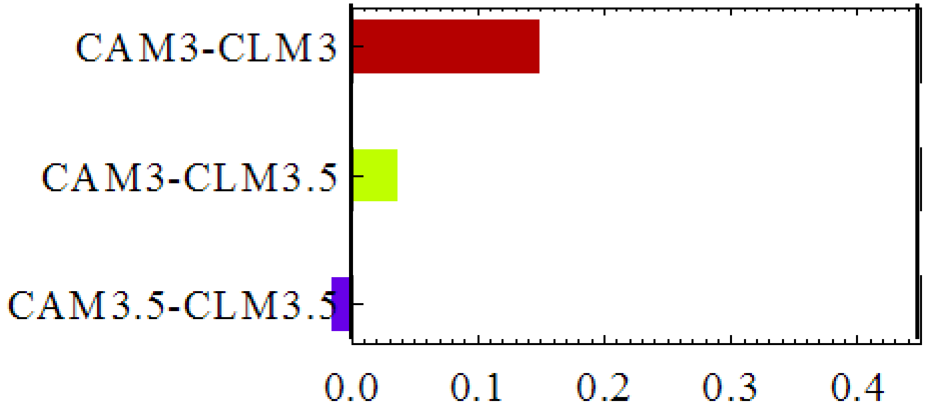
Broader impacts: CLM3 → CLM3.5



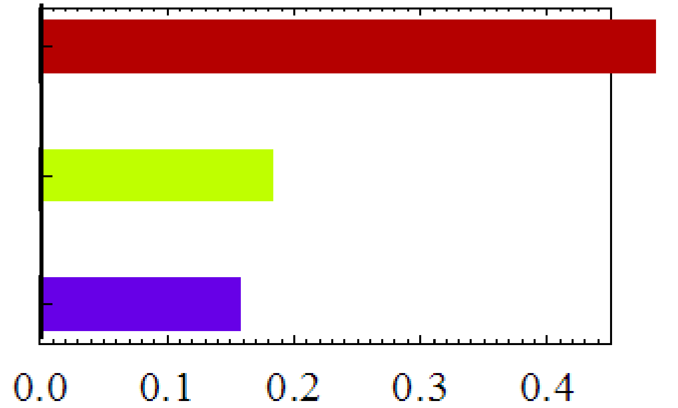
Impact on land-atmosphere interactions

Global average $\Delta\Omega$

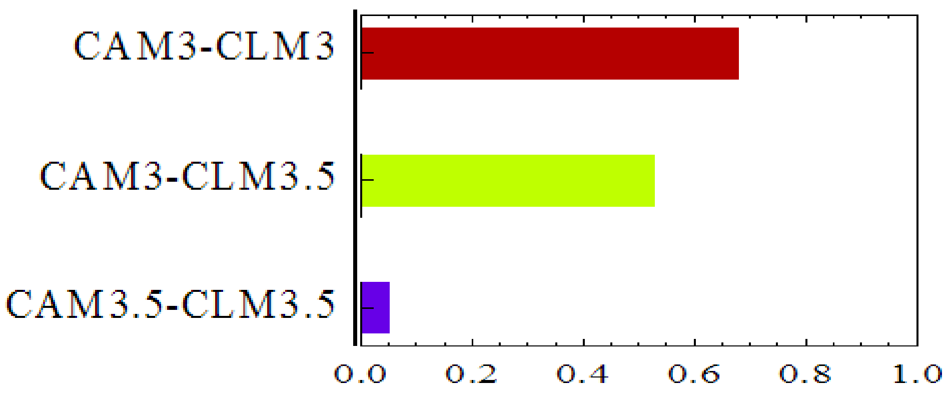
SM-Precipitation



SM-Evaporation



Evaporation - Precipitation

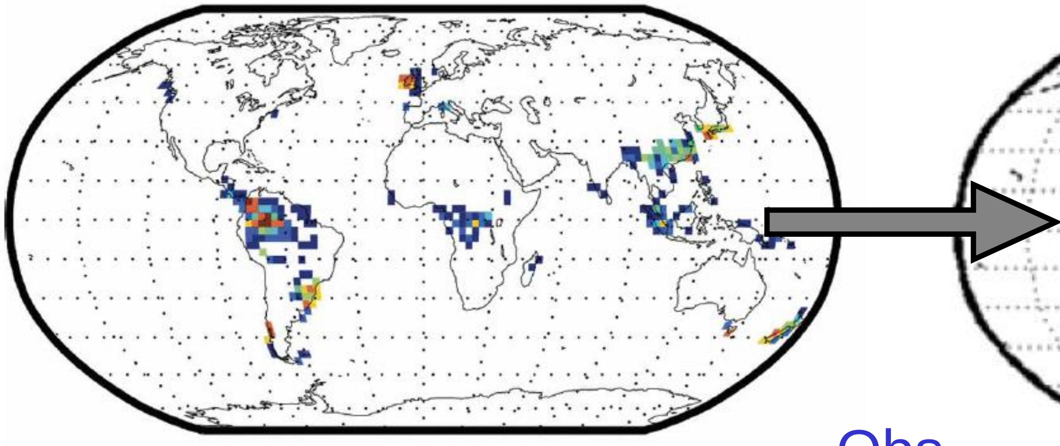


Shift from moisture-limited to energy-limited ET regime

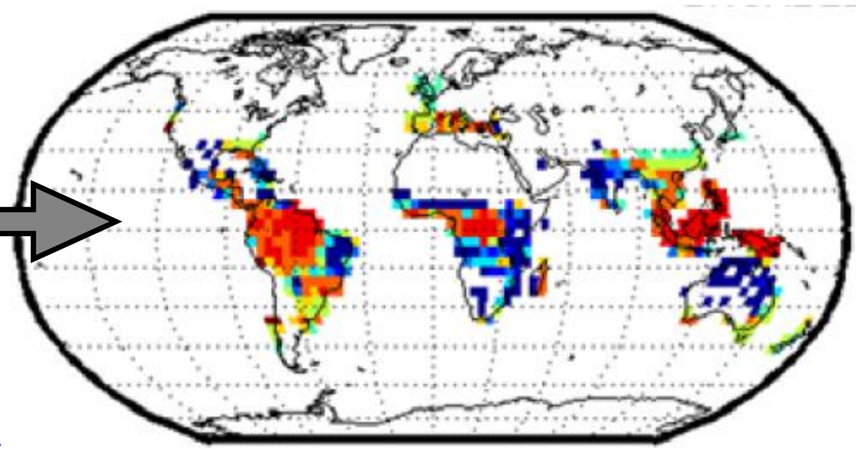
Impact on global vegetation distribution

Broadleaf evergreen tree

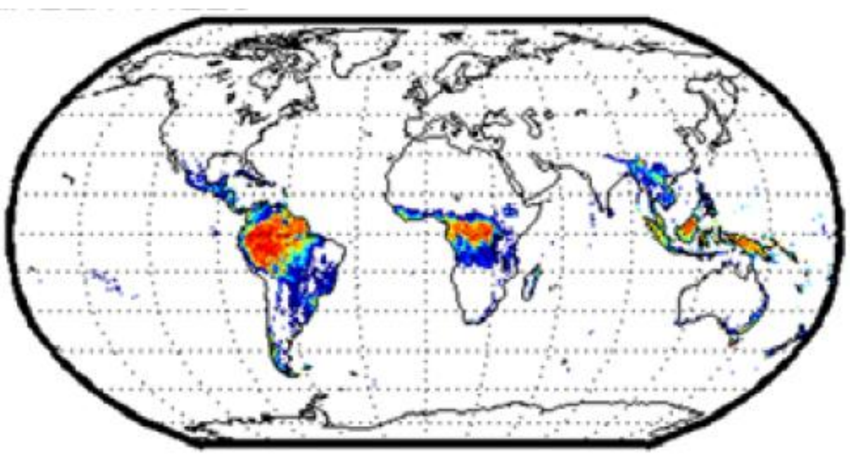
CLM 3.0



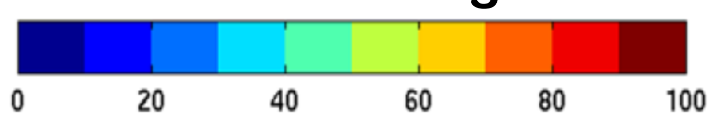
CLM 3.5



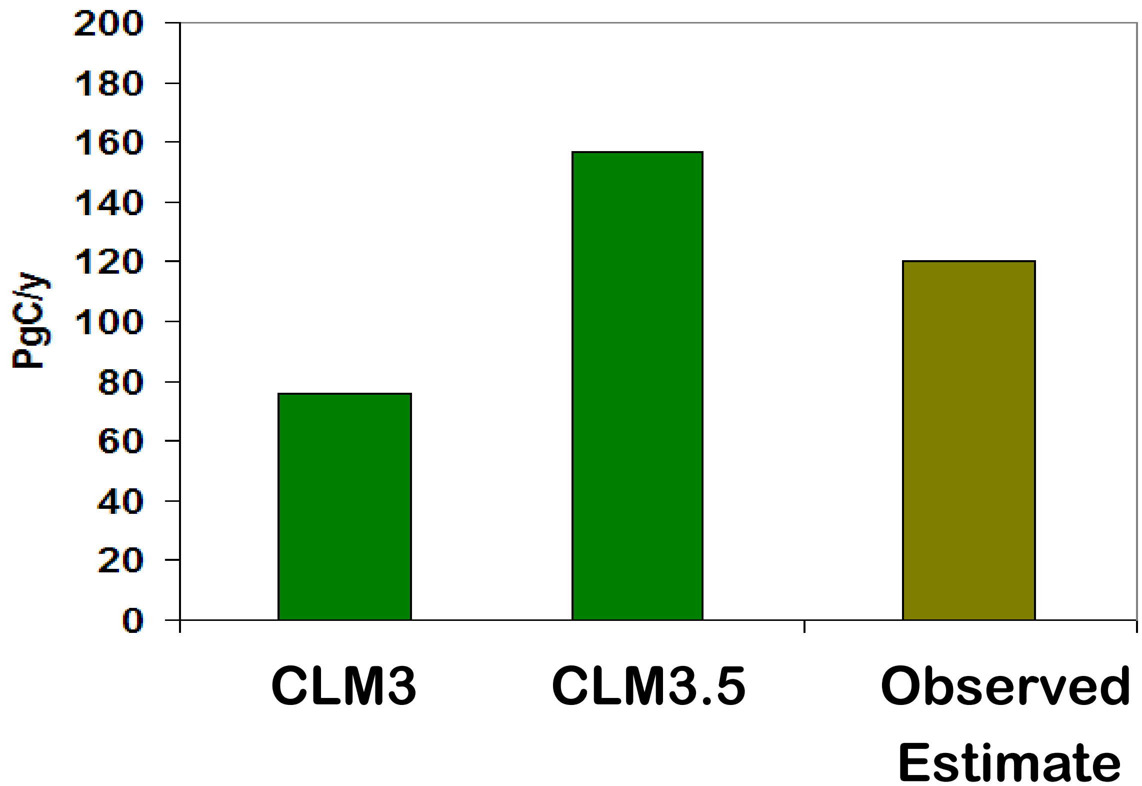
Obs



% Veg cover



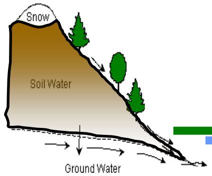
Impact on Photosynthesis (GPP)



Overproductivity may reflect soils that are now too wet

Summary of improvements: CLM3 → CLM3.5

- Alleviated vegetation underproductivity
  - Permits CLM-CN development to proceed
- Improved potential vegetation biogeography
  - Vegetation distribution not as sensitive to precipitation
- Improved partitioning of evapotranspiration
- Improved seasonal soil moisture storage
- Added functionality, e.g. groundwater model
- Improved phase of runoff annual cycle
- More realistic prescribed surface characterization



CLM3.5 is alright, but …

Recommendations from Xubin Zeng's group

1. Soil moisture (SM) Richards equation

Comment: Numerical solution cannot maintain the steady state solution of the differential equation

Solution: Revised form of the Richards equation (Zeng and Decker 2008)

2. SM variability and water table depth (WTD)

Comment: CLM 3.5 has unrealistic vertical distribution of SM variability and its SM and WTD incorrectly depend on grid structure

Solution: New and simple bottom condition (Decker and Zeng 2008)

3. Surface resistance (rs) and ground evaporation

Comment: CLM3.5's rs improves simulations, but its formulation is inappropriate

Solution: Dead-leaf resistance and under-canopy turbulent stability (Sakaguchi and Zeng 08)

4. Soil ice fraction

Comment: Based on Noah, CLM3.5's formulation is too sensitive to 'B' parameter

Possible Alternative: a new formulation (Decker and Zeng 2006)

5. Convergence of canopy roughness length (Z_o)

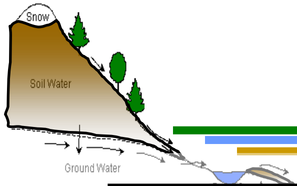
Comment: Z_o does not change for LAI from 0 to 7

Solution: A new formulation for this convergence (Zeng and Wang 2007)

6. Snow burial fraction

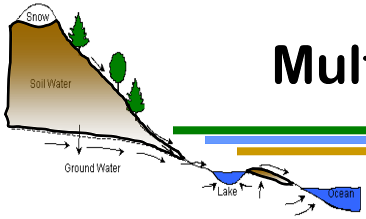
Comment: CLM3.5 does not distinguish snow over short veg. versus snow under trees

Solution: A new formulation (Wang and Zeng 2008)

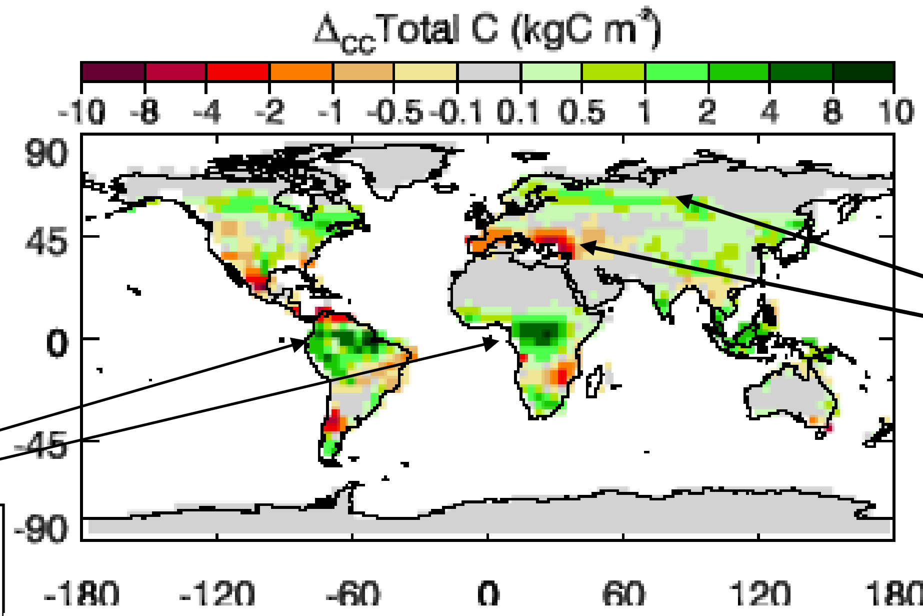


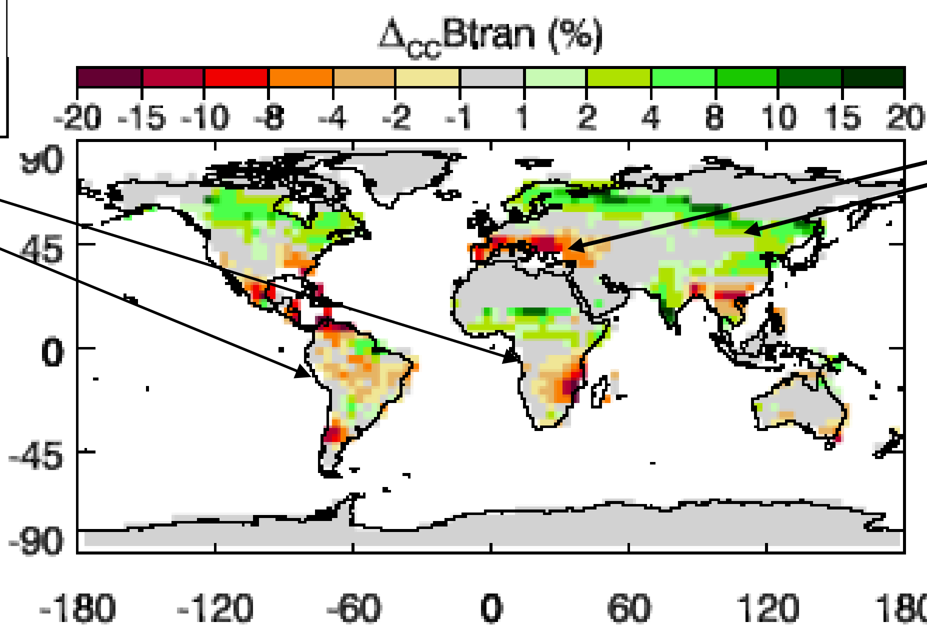
CLM3.5 → CLM4 even more collaborative (?)

- **Projects**
  - more hydrology, snow (including black carbon on snow), permafrost, urban, fine-mesh, numerous minor corrections, (ice sheet), (CN and CNDV)
- **Institutions**
  - U. Alaska, U.C. Irvine, U. Texas at Austin, U. Arizona, ORNL, CU, U. Wisconsin, CSU, U. Kansas, G. Tech, Kings College, LANL
- **External collaborators**
  - J. Feddema, T. Jackson, M. Flanner, C. Zender, V. Romanovsky, A. Slater, D. Nicolsky, V. Alexeev, B. Sacks, X. Zeng, M. Decker, A. Wang, G. Niu, L. Yang, L. Gulden, T. Jackson, S. Grimmond, P. Lawrence, R. Stöckli, F. Hoffmann, B. Lipscomb, S. Running, B. Dickinson
- **NCAR staff**
  - K. Oleson, S. Levis, G. Bonan, P. Thornton, D. Lawrence, D. Gochis, A. Hahmann, P. Thornton, S. Swenson, E. Kluzek, N. Rosenbloom, J. Lee, T. Craig



Multiple factors control the climate-carbon cycle feedback:





Tropics: nutrient mineralization from warming can offset effect of drier soils

Temperate zone: source/sink relationship correlates well with changes in soil moisture

Thornton et al., in prep

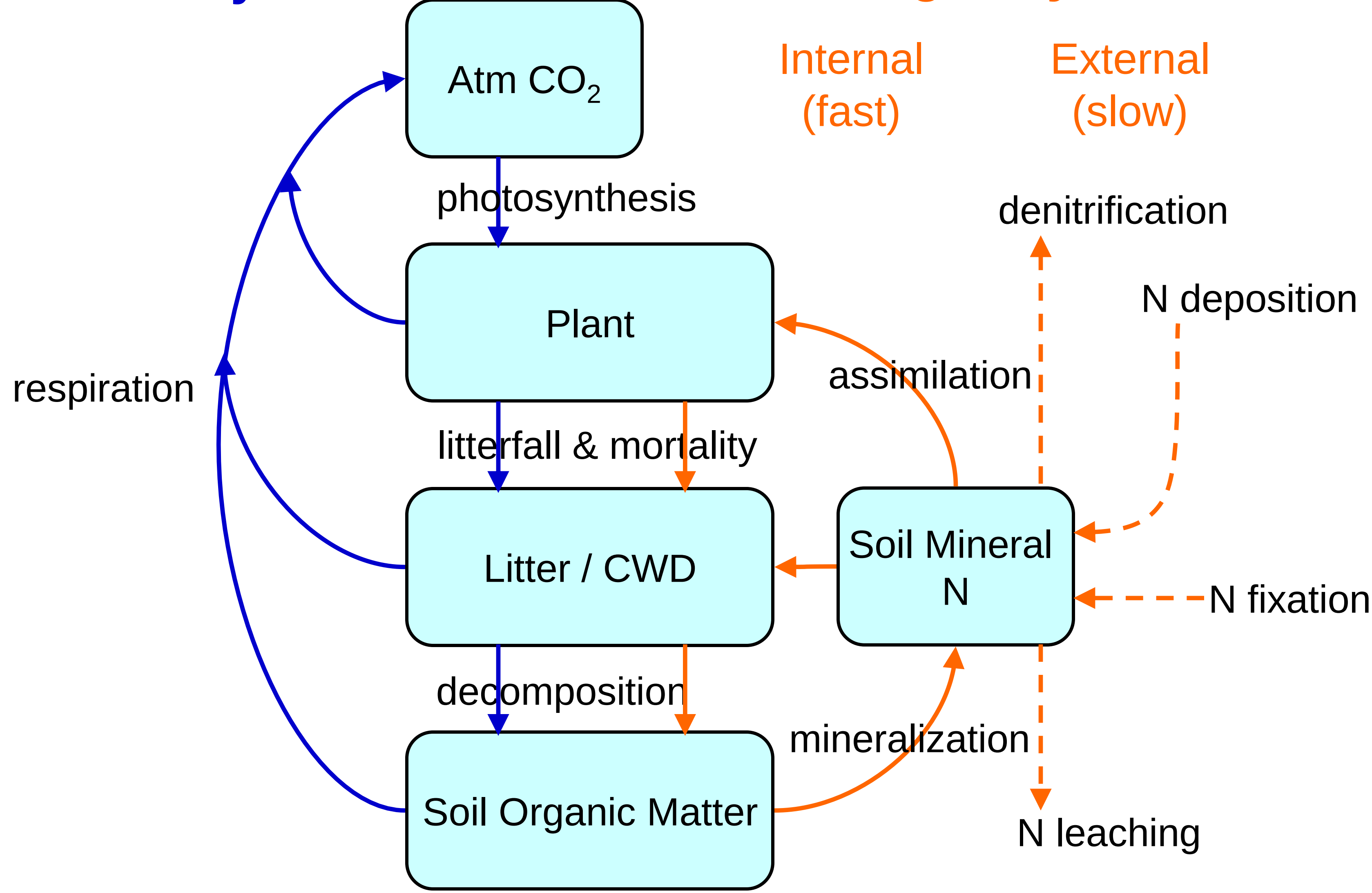
CLM4 will be a much improved platform from which we can continue and expand our research on the role of land processes in climate and climate change

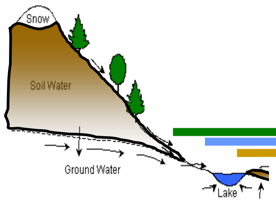
- Land-atmosphere interaction
- Water resources
- Terrestrial carbon cycle, dynamic vegetation biogeography
- Land cover/land use, urbanization
- Fire, dust, permafrost
- Geoengineering

CLM – CN: carbon and nitrogen cycling

Carbon cycle

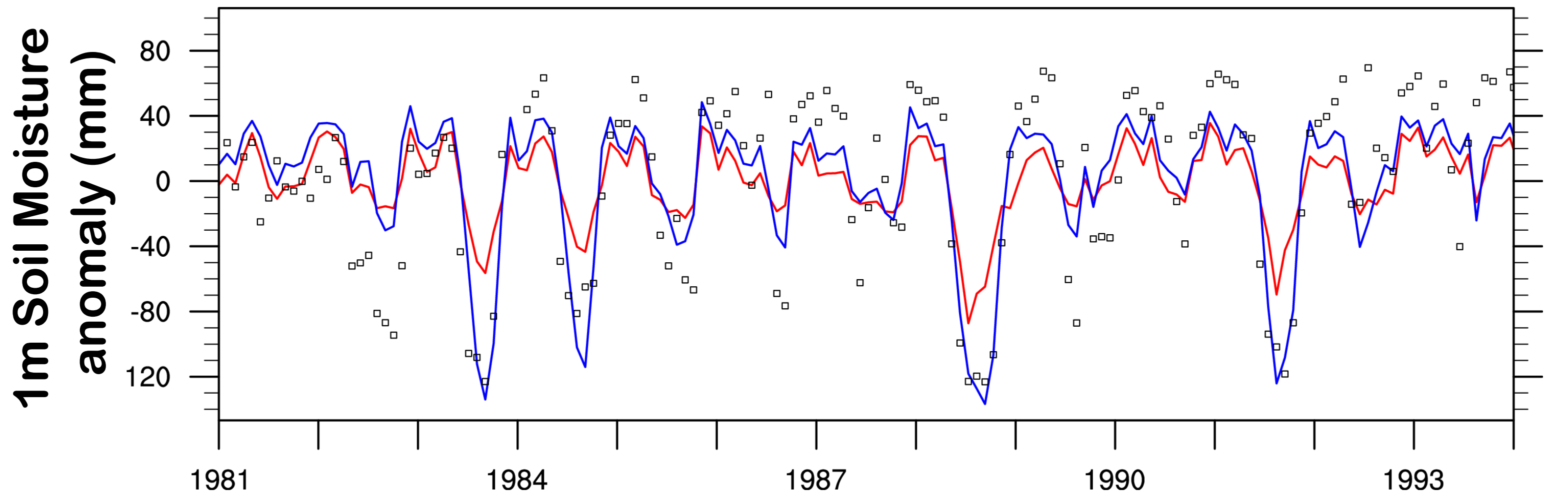
Nitrogen cycle





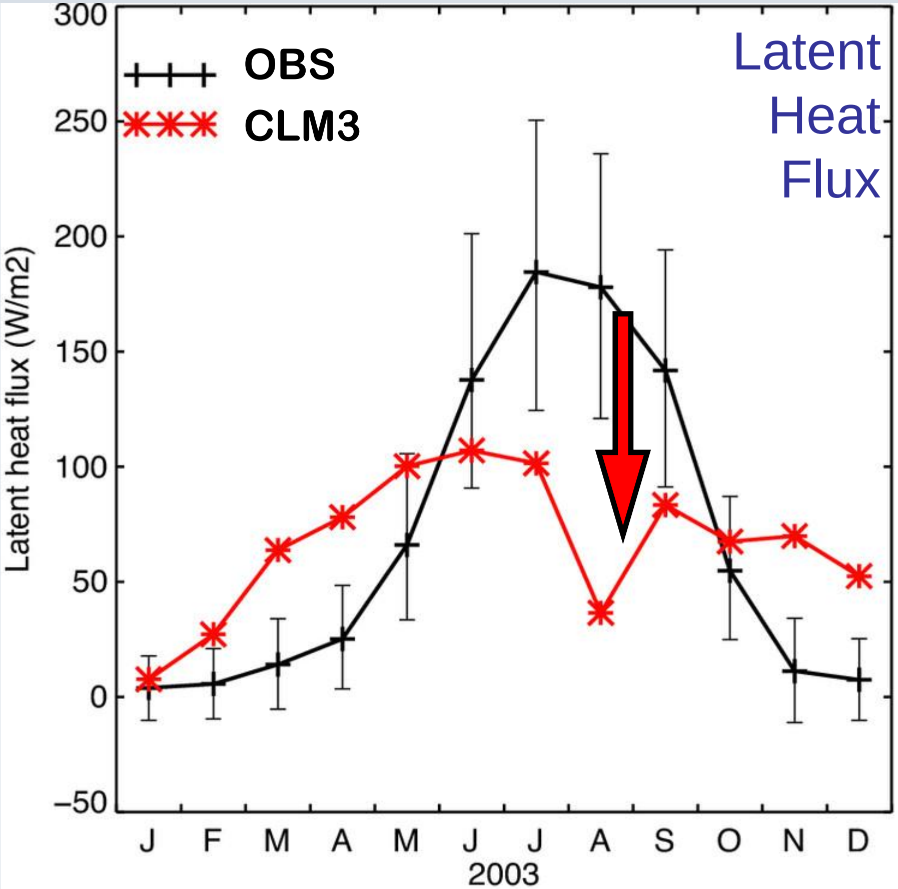
Soil moisture variability

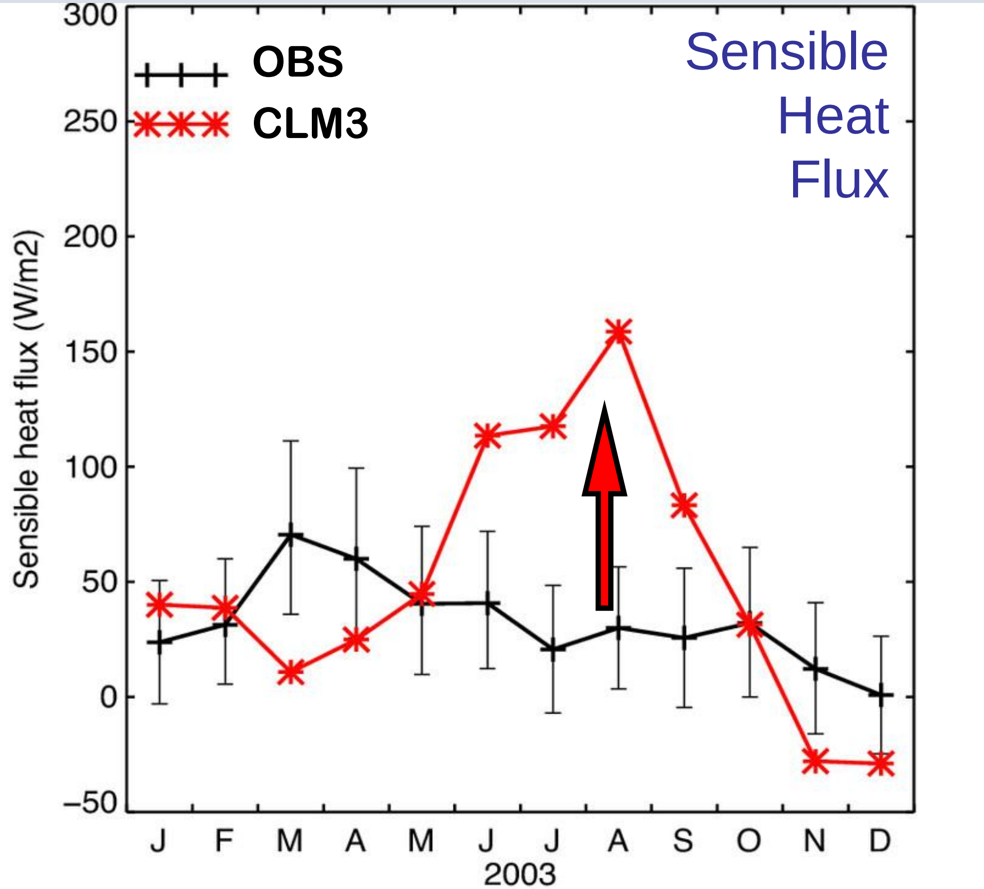
Bondville, IL



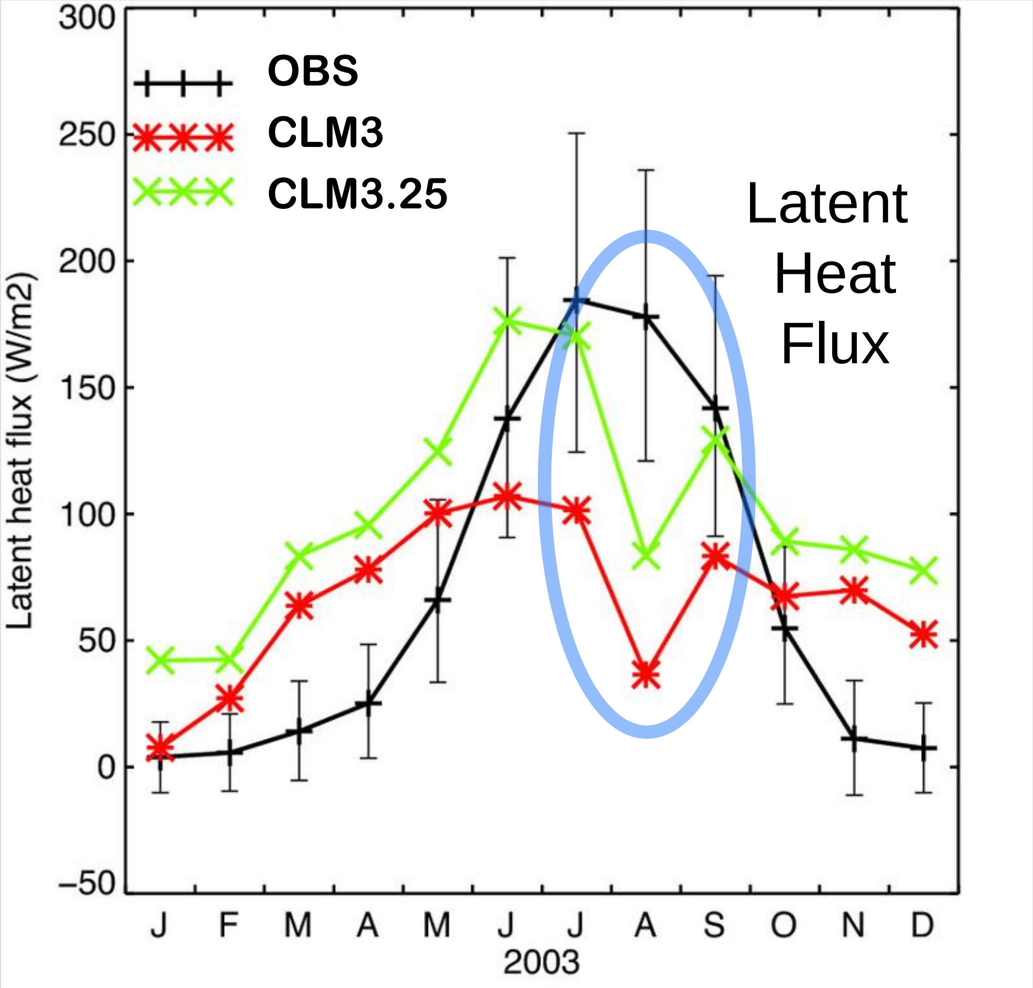
- **19 Illinois stations, 1981-2004**
  - **Median $\sigma_{model} / \sigma_{obs}$: 0.44 → 0.72**
- **Rooting zone soil moisture variability increased globally**
- **Appears to alleviate vegetation overproductivity of mid-latitude FLUXNET sites in CN mode?**
- **Recover seasonal soil moisture stress → impact on variability of surface turbulent fluxes**

Morgan Monroe State Forest tower site





Morgan Monroe State Forest tower site



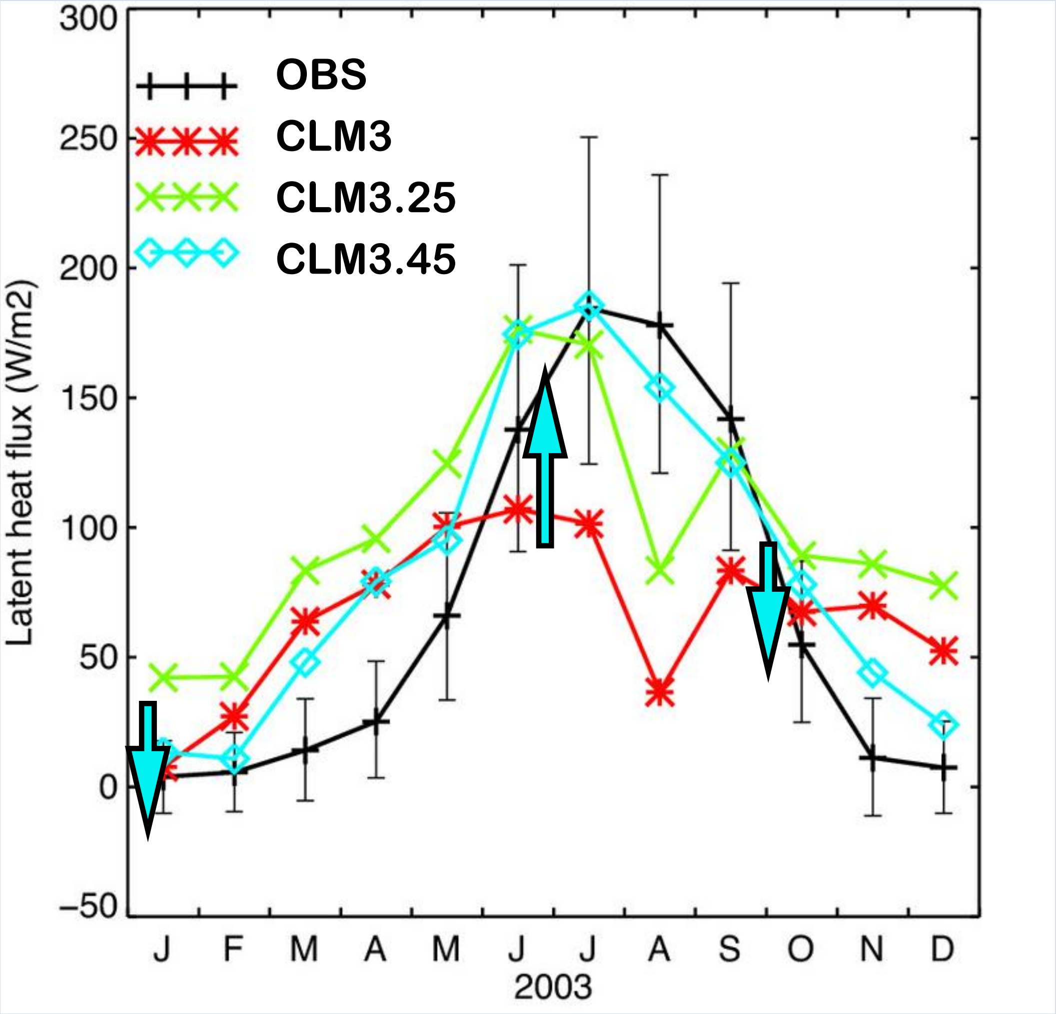
<u>Reduced canopy interception</u>

Permits more water to enter soil

<u>Groundwater/aquifer model</u>

Stores/releases moisture on seasonal-decadal timescales

Morgan Monroe State Forest tower site

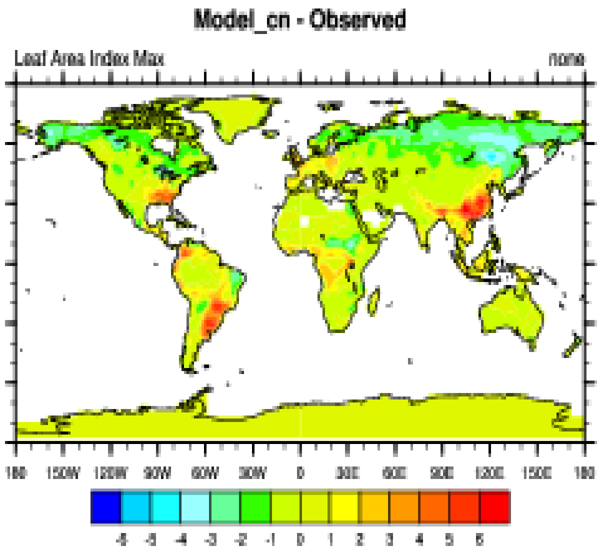


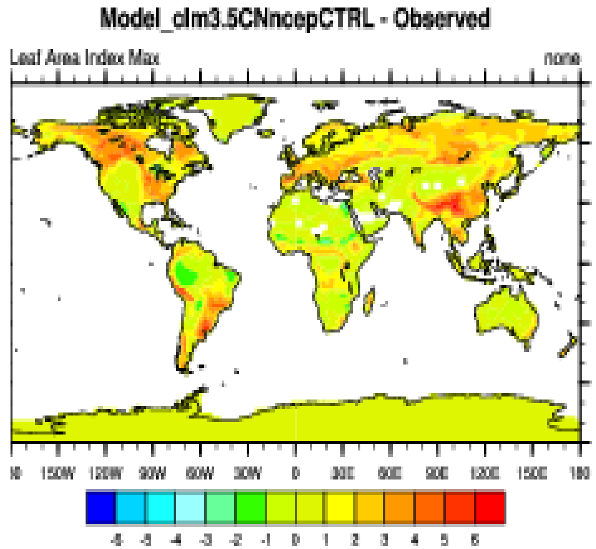
- decreases LH in spring, more water available in summer for transpiration

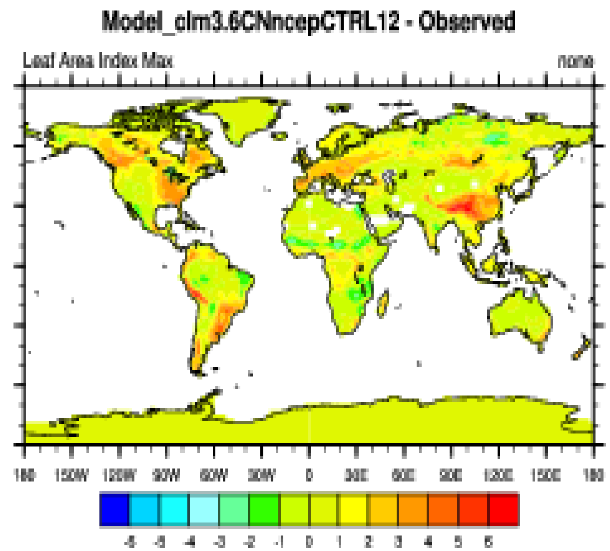
Stöckli et al. , JGR-BGC (2008)

Reducing LAI biases in CLM-CN through C-LAMP

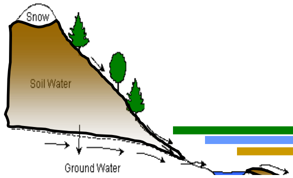
CLM-CN LAI minus MODIS LAI





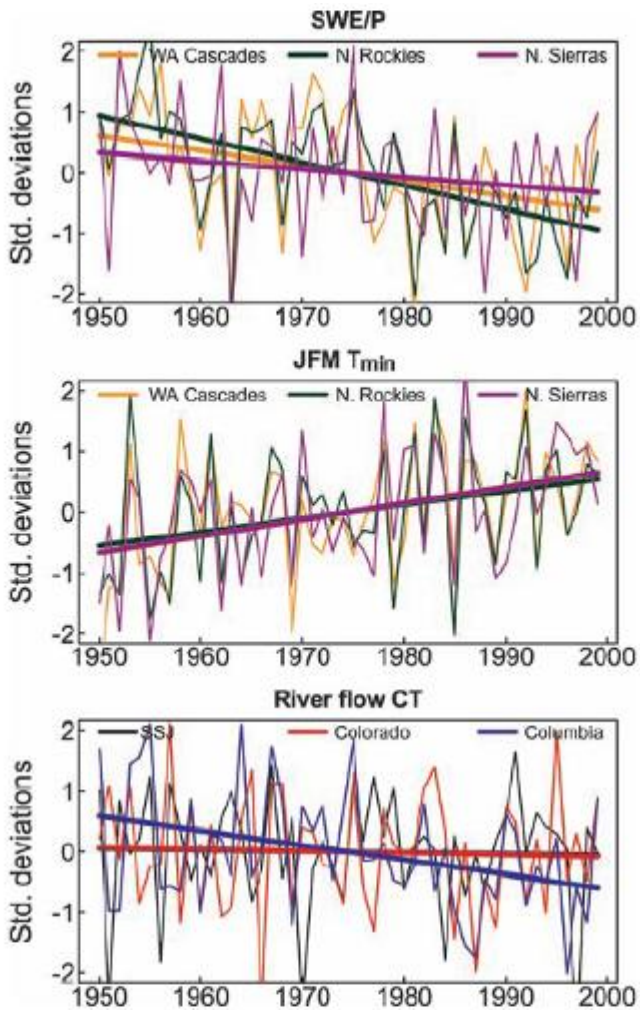


v. 3.1 → v. 3.5 → v. 3.6

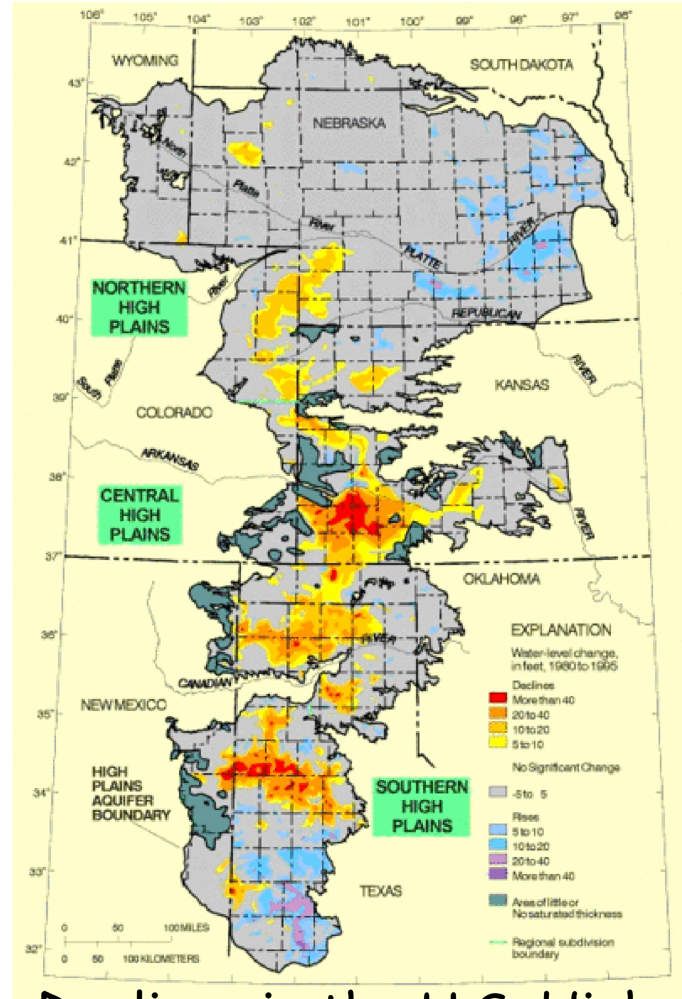


Water Management Impacts

less snow = less flow or
less snow = less storage ??

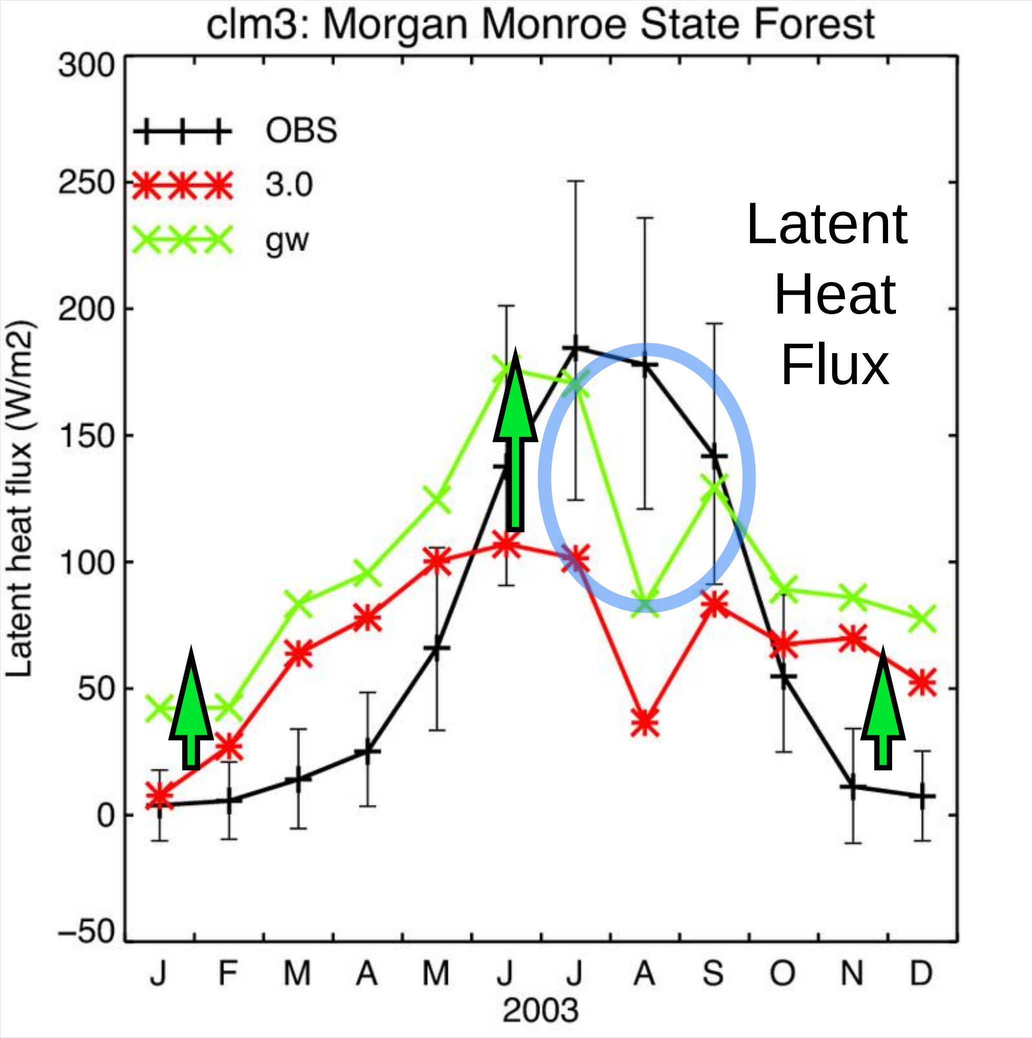


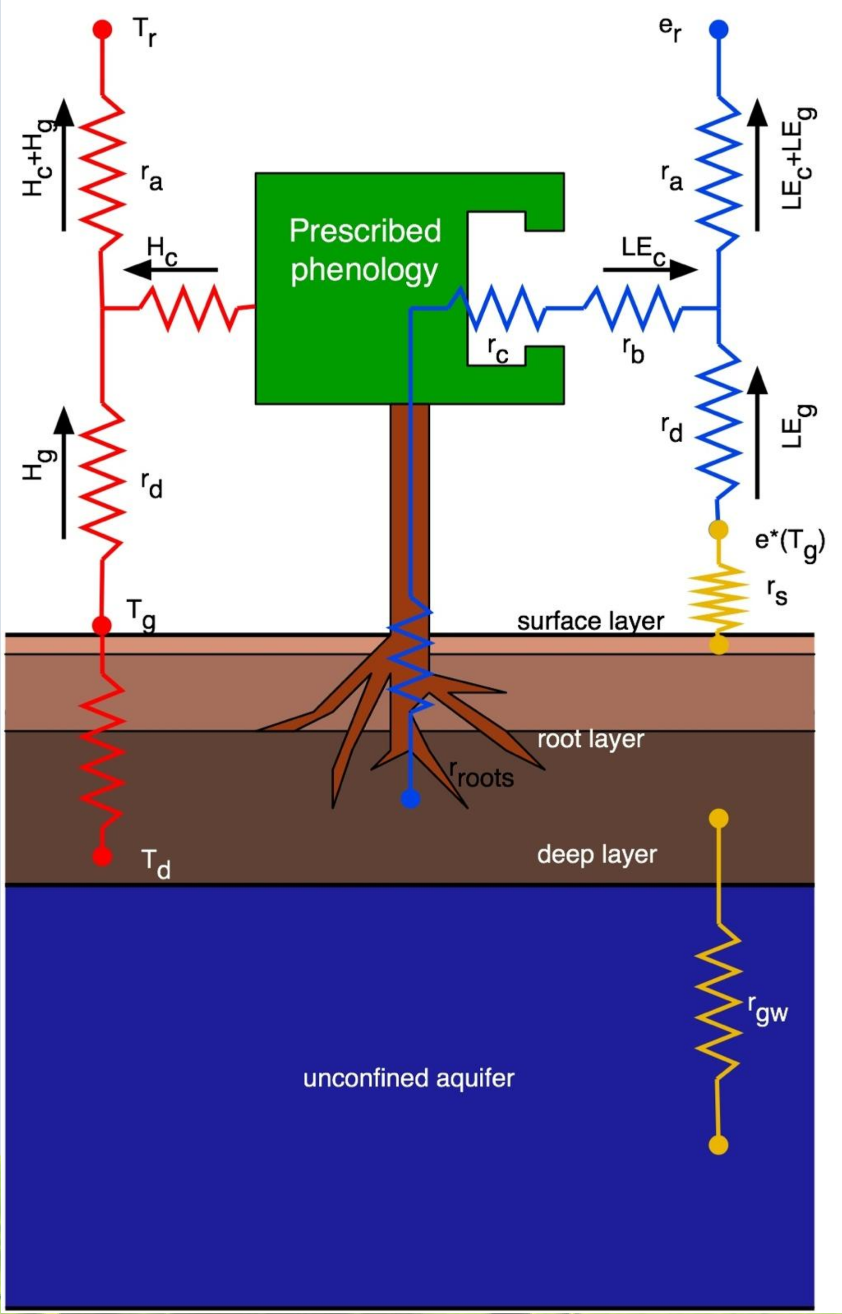
Barnett et al., 2008, Science



Declines in the U.S. High Plains Aquifer : A vanishing water 'source'…

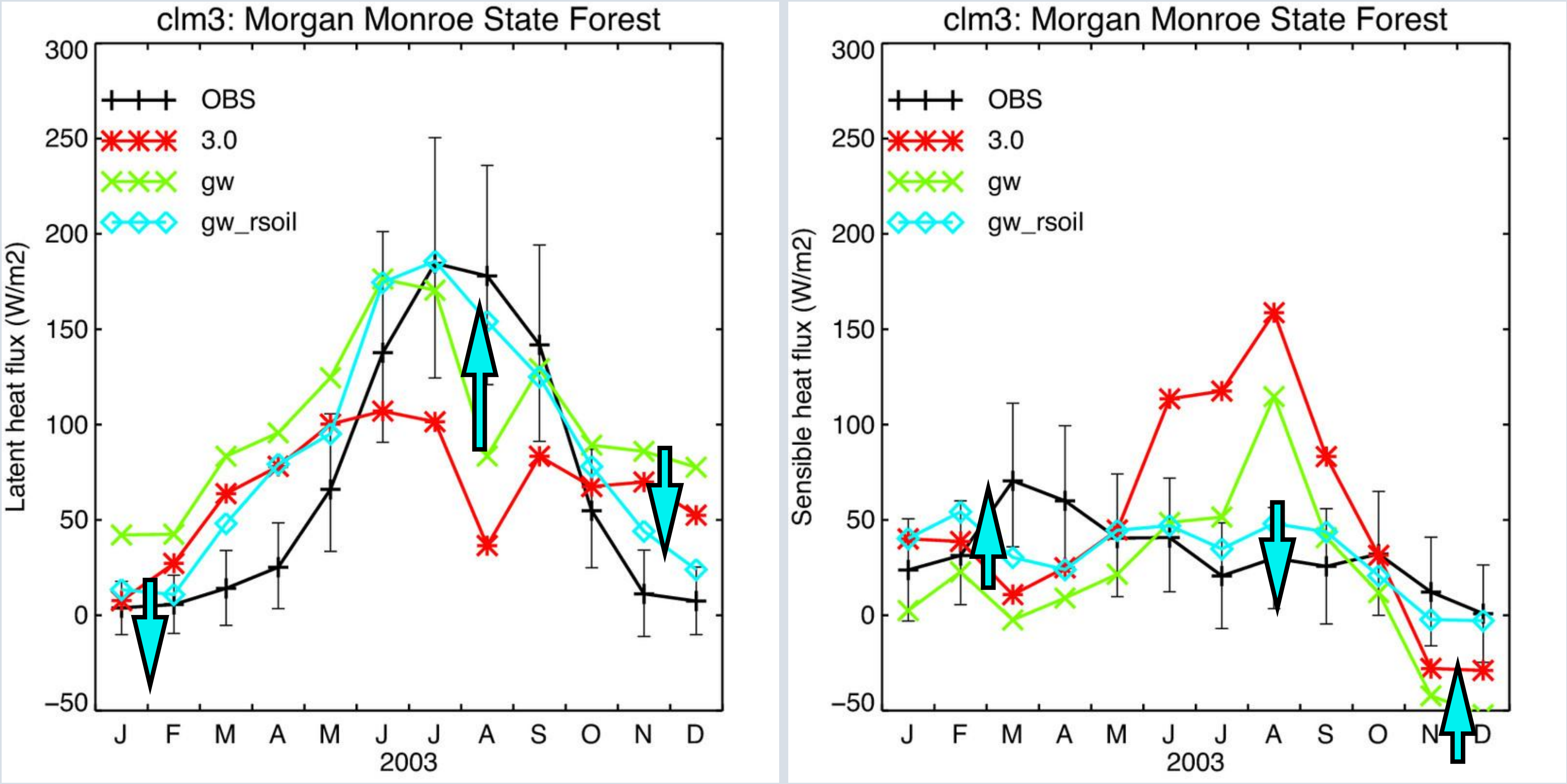
Addition of an ground water model





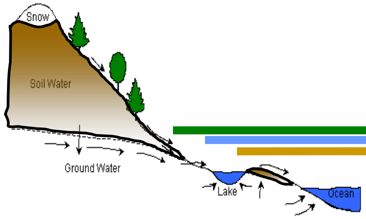
- stores/releases water on seasonal-decadal scale

Addition of a soil evaporation resistance



- decreases LE in spring, more water in summer
- more realistic H, and therefore bowen ratio

Stöckli et al. , JGR-BGC (2008)



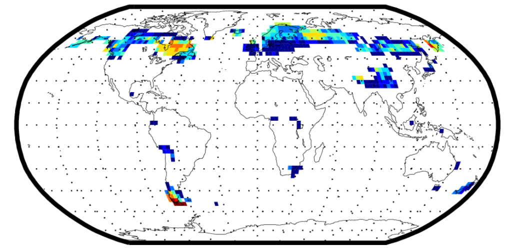
Hydrology biases and vegetation

The coupled CAM3/CLM3-DGVM cannot simulate a forest in eastern U.S.

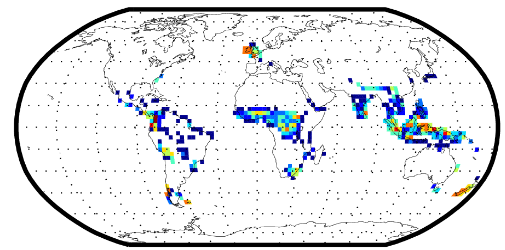
Uncoupled CLM3-DGVM simulations demonstrate the sensitivity of vegetation to precipitation

Precipitation (% observed)	Tree (%)	Grass (%)	Bare (%)
100%	59	39	2
90%	51	47	2
80%	31	67	2
70%	16	81	3
60%	4	88	8

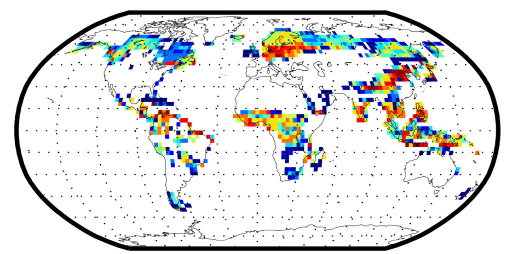
Needleleaf Evergreen Trees



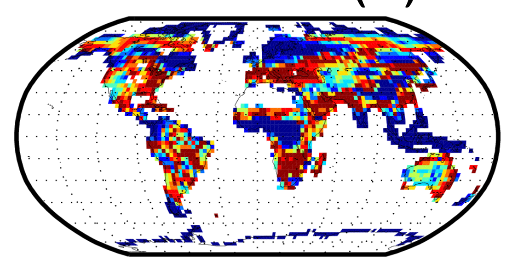
Broadleaf Deciduous Trees (



Other Deciduous Trees (%)



Grasses (%)



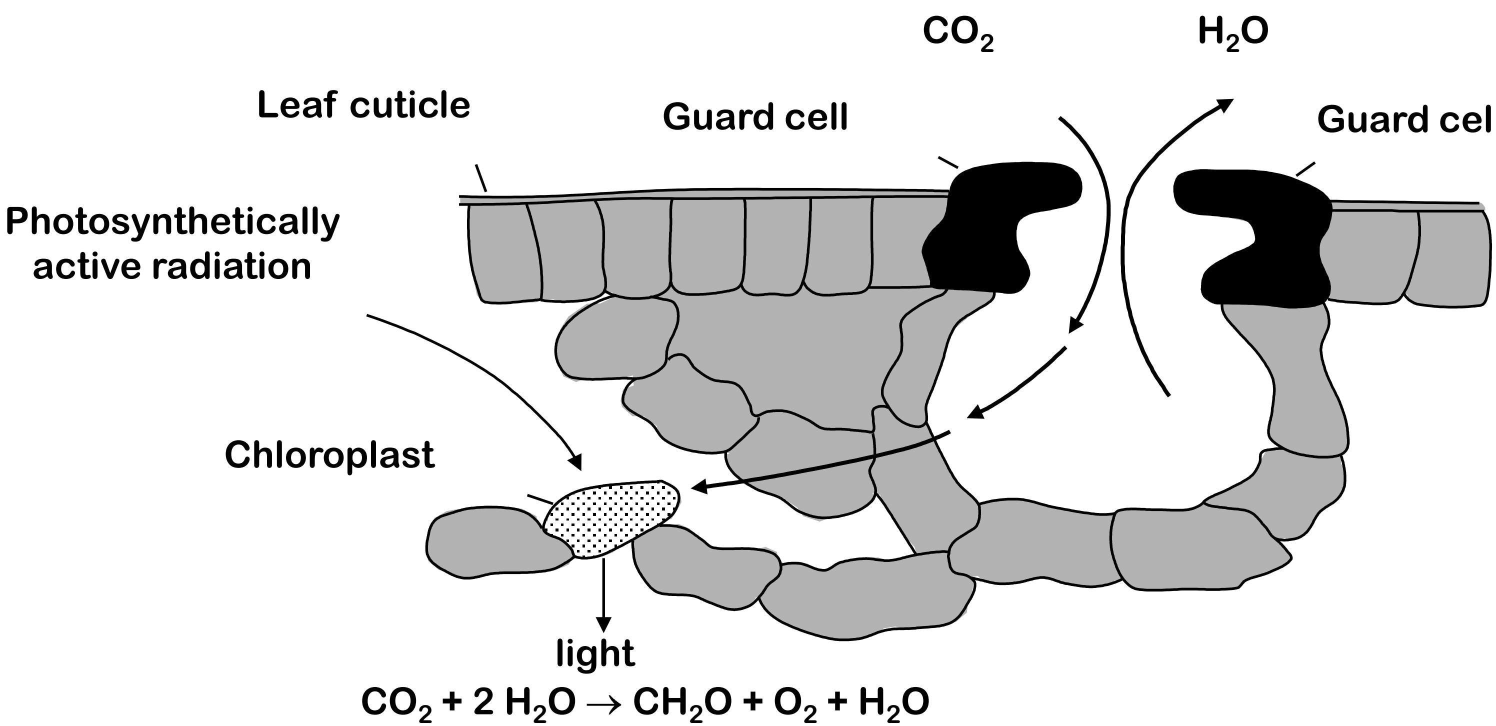
Bonan & Levis (2006) J. Climate, CCSM special issue

3rd Generation: Photosynthesis models

Plant physiological controls on evapotranspiration

Function of solar radiation, humidity deficit, soil moisture, [CO2], temperature

Stomatal Gas Exchange

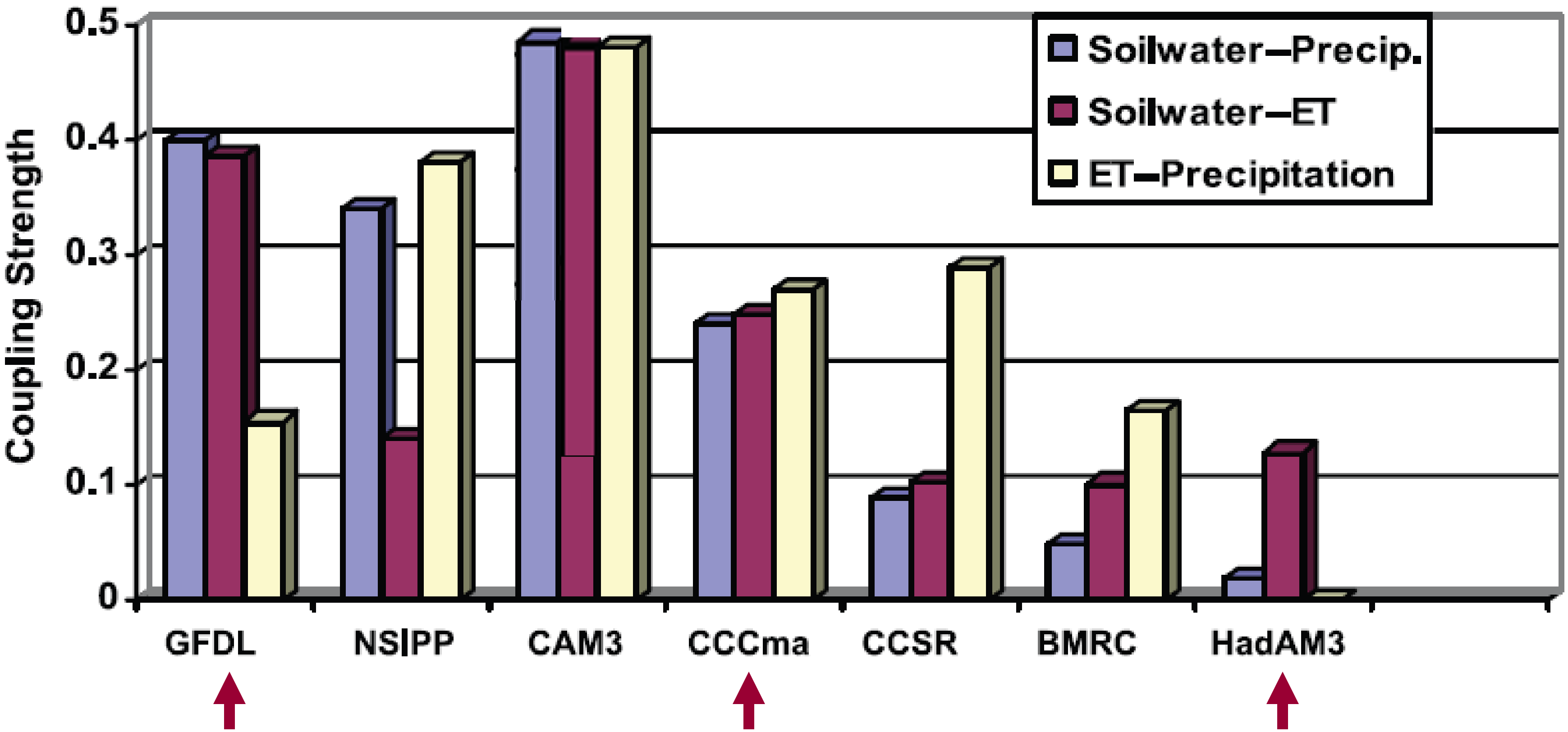


Bonan (1995) JGR 100:2817-2831
Denning et al. (1995) Nature 376:240-242
Denning et al. (1996) Tellus 48B:521-542, 543-567
Cox (1999)

Figure courtesy G. Bonan

Impact on land-atmosphere interactions

GLACE: To what extent does soil moisture influence the overlying atmosphere and the generation of precipitation?



Koster et al., 2004; IPCC